



# THE MISSION ACCESSIBLE NEAR-EARTH OBJECTS SURVEY (MANOS): FIRST PHOTOMETRIC RESULTS

A. THIROUIN<sup>1</sup>, N. MOSKOVITZ<sup>1</sup>, R. P. BINZEL<sup>2</sup>, E. CHRISTENSEN<sup>3</sup>, F. E. DEMEO<sup>2</sup>, M. J. PERSON<sup>2</sup>, D. POLISHOOK<sup>4</sup>, C. A. THOMAS<sup>5,6</sup>,  
D. TRILLING<sup>7</sup>, M. WILLMAN<sup>8</sup>, M. HINKLE<sup>7</sup>, B. BURT<sup>1</sup>, D. AVNER<sup>7</sup>, AND F. J. ACEITUNO<sup>9</sup>

<sup>1</sup> Lowell Observatory, 1400 W Mars Hill Rd, Flagstaff, AZ 86001, USA; [thirouin@lowell.edu](mailto:thirouin@lowell.edu)

<sup>2</sup> Massachusetts Institute of Technology (MIT), 77 Massachusetts Avenue, Cambridge, MA 02139, USA

<sup>3</sup> University of Arizona, Tucson, AZ, USA

<sup>4</sup> Department of Earth and Planetary Science, Weizmann Institute, Herzl St 234, Rehovot, 7610001, Israel

<sup>5</sup> Planetary Science Institute (PSI), 1700 E Fort Lowell Road 106, Tucson, AZ 85719, USA

<sup>6</sup> USRA/NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA

<sup>7</sup> Department of Physics and Astronomy, P.O. Box 6010, Northern Arizona University, Flagstaff AZ 86001, USA

<sup>8</sup> University of Hawaii, Pukalani, HI 96788, USA

<sup>9</sup> Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía, S/N, Granada, E-18008, Spain

Received 2016 May 31; revised 2016 July 9; accepted 2016 July 12; published 2016 November 11

## ABSTRACT

The Mission Accessible Near-Earth Objects Survey aims to physically characterize sub-km near-Earth objects (NEOs). We report the first photometric results from the survey that began in 2013 August. Photometric observations were performed using 1–4 m class telescopes around the world. We present rotational periods and light curve amplitudes for 86 sub-km NEOs, though in some cases only lower limits are provided. Our main goal is to obtain light curves for small NEOs (typically, sub-km objects) and estimate their rotational periods, light curve amplitudes, and shapes. These properties are used for a statistical study to constrain overall properties of the NEO population. A weak correlation seems to indicate that smaller objects are more spherical than larger ones. We also report seven NEOs that are fully characterized (light curve and visible spectra) as the most suitable candidates for a future human or robotic mission. Viable mission targets are objects fully characterized, with  $\Delta v^{\text{NHATS}} \leq 12 \text{ km s}^{-1}$ , and a rotational period  $P > 1 \text{ hr}$ . Assuming a similar rate of object characterization as reported in this paper, approximately 1230 NEOs need to be characterized in order to find 100 viable mission targets.

*Key words:* minor planets, asteroids: general

## 1. INTRODUCTION

Near-Earth objects (NEOs) are minor bodies (asteroids, comets, meteoroids) on orbits with perihelia distances  $q < 1.3 \text{ AU}$ . As of 2016 April, 14,263 NEOs have been discovered.<sup>10</sup> About 90% of NEOs originated in the asteroid belt and have a rocky nature (Jewitt 2002; DeMeo & Binzel 2008). Despite the impressive number of discovered NEOs, physical information about these objects remains limited. Rotational light curves are one tool to constrain their physical evolution. The rotational states of asteroids provide information about physical properties such as a lower limit to density, internal structure, cohesion, and shape or surface heterogeneity (Pravec & Harris 2000; Holsapple 2001, 2004).

Large objects (diameter greater than 1 km) have been well-studied with photometric, spectroscopic, and/or radar techniques (Binzel et al. 2002, p. 255; Pravec et al. 2002, p. 113; Warner et al. 2009; Thomas et al. 2014, 2011; Benner et al. 2015, p. 165), but small objects are also of interest for a number of reasons. First, objects in the meter to decameter size regime can impact the Earth on human timescales, as opposed to the  $10^6$  years impact interval of km-scale objects (Harris & D’Abramo 2015). As evidenced in Chelyabinsk, Russia in 2013 (Popova et al. 2013) relatively small objects can pose a modest impact hazard. In addition, these small NEOs are the immediate parent bodies of meteorites. To interpret meteorites

in an astrophysical context requires that we better understand their source population. In addition, studying these small objects can provide deeper insight into size-dependent evolutionary processes such as the radiative Yarkovsky and Yarkovsky–O’Keefe–Radzievskii–Paddack (YORP) effects (Bottke et al. 2006). Finally, the much greater number of NEOs with sizes of  $\sim 100 \text{ m}$  compared to km-size objects provides more opportunities for detailed physical study. This includes increased possibilities for a variety of exploration mission scenarios (e.g., Abell et al. 2009) as well as more frequent near-Earth encounters to study physical changes associated with gravitational perturbation events (e.g., Scheeres et al. 2005; Binzel et al. 2010).

Because NEOs have their origin in the Main Belt of asteroids, and are the result of multiple collisions, their shape as well as rotational properties are valuable tracers of their evolution. Binzel et al. (2002, p. 255) suggested that NEOs should be similar in rotation and shape to similar-sized Main Belt asteroids, and spin distribution of km-size Main Belt asteroids and similar sized NEOs supports this assertion (Pravec et al. 2008; Polishook & Brosch 2009). Therefore, the study of small NEOs (sub-km objects) allows us to infer the properties of small Main Belt asteroids, which remain unobservable with current facilities.

We present here a study focused on the rotational properties of sub-km NEOs. Our ultimate goal is to obtain the most comprehensive data-set of sub-km NEOs to date, allowing a homogeneous and detailed study of the shape, surface and rotational properties of these objects. This paper is divided into

<sup>10</sup> Numbers from the Minor Planet Center: <http://www.minorplanetcenter.net/>.

six sections. In the next section, we introduce briefly the Mission Accessible Near-Earth Objects Survey (MANOS). Then, we describe the observations and the data set analyzed. In Section 4, we present our main results regarding rotational period and light curve amplitudes of our targets. In Section 5, we discuss our results and compare them to the literature. In Section 6, we put constraints on the internal structure of NEOs. Finally, Section 7 is dedicated to the summary and conclusions of this work.

## 2. WHAT IS MANOS?

The Mission Accessible Near-Earth Objects Survey (MANOS) began in 2013 August as a multi-year survey program (2013B-2016B) awarded by the National Optical Astronomy Observatory (NOAO), and funded through NASA NEOO (Near-Earth Object Observations) office. MANOS is a physical characterization survey of NEOs providing physical data for several hundred mission accessible NEOs across visible and near-infrared wavelengths (N. Moskovitz et al. 2016, in preparation). This comprehensive study aims to provide light curves, astrometry, and reflectance spectra. MANOS primarily focuses on newly discovered objects. Targets for MANOS are selected based on two other criteria (besides observability): (i) mission accessibility (i.e.,  $\Delta v^{\text{SH}} < 7 \text{ km s}^{-1}$  (see below for more details)), and (ii) absolute magnitude greater than 20 (i.e., objects with a diameter smaller than  $\sim 300 \text{ m}$  assuming an albedo of 0.2). Typical NEOs are discovered at  $V \sim 20$  and fade by 3.5 mag after one month, thus their characterization requires a challenging set of rapid response observations (Galache et al. 2015). For such a rapid response, MANOS employs 1–8 m class facilities in the Northern and Southern Hemispheres through queue, remote, or in situ observations. Currently, we have the capacity to characterize between 5 and 10 newly discovered objects per month. Large telescopes allow us to obtain rotational light curves for objects down to  $V \sim 22 \text{ mag}$ , and visible spectra down to  $V \sim 20.5 \text{ mag}$ .

MANOS was initially awarded time on the 8.1 m Gemini Telescopes (Northern and Southern Hemispheres), the 4.1 m Southern Astrophysical Research (SOAR) telescope, the 4 m Mayall Telescope (Kitt Peak Observatory), and the 1.3 m Small and Moderate Aperture Research Telescope System (SMARTS) telescope. We have also employed facilities at Lowell Observatory and the University of Hawaii. Gemini and University of Hawaii facilities are dedicated to spectroscopic observations and will not be presented here.

Figure 1 shows all published NEO light curves reported in the light curve database of Warner et al. (2009) as of 2015 July. The peak of the distribution is at an absolute magnitude  $H \sim 17\text{--}18$ , i.e., objects with diameter of approximately 1 km (assuming an albedo of 0.2; albedo value used for this entire paper). At greater  $H$ , the number of objects studied for rotational properties is low. In the first  $\sim 2$  years of our survey, we have doubled the number of photometrically characterized objects with an absolute magnitude  $H = 23.5\text{--}25.5$ , and increased by 300% the number of objects in the range of  $H = 25.5\text{--}26.5$ .

As mentioned, one of our main selection criteria is the mission accessibility. The *Asteroid Redirect Mission* is a potential future space mission proposed by NASA (Mazanek et al. 2015). As of mid-2016 the outline of this mission is to rendezvous with a “large” near-Earth asteroid, use robotic arms

to retrieve a boulder up to 4 m in size from the surface and then return it to cis-lunar orbit where it can be studied in situ by astronauts.

A key parameter for a mission to a NEO (and by extension all missions) is the delta- $v$  ( $\Delta v$ ) required to reach the orbit of the object. This parameter is the change in velocity needed to go from low Earth orbit (LEO) to a NEO rendez-vous using a Hohman transfer orbit. In first approximation, the LEO–NEO  $\Delta v$  values are computed using the Shoemaker & Helin (1978) formalism ( $\Delta v^{\text{SH}}$ ). On 2016 April, 14,263 NEOs are known, and only 13 objects have a  $\Delta v^{\text{SH}} < 4 \text{ km s}^{-1}$ , 145 have a  $\Delta v^{\text{SH}} < 4.5 \text{ km s}^{-1}$ , and 625 with a  $\Delta v^{\text{SH}} \leq 5 \text{ km s}^{-1}$ .<sup>11</sup>

In Table 1, the  $\Delta v^{\text{SH}}$  of MANOS objects are reported. MANOS observed five objects with a  $\Delta v^{\text{SH}}$  lower than  $4 \text{ km s}^{-1}$ , four objects with a  $\Delta v^{\text{SH}}$  between 4 and  $4.5 \text{ km s}^{-1}$ , and 23 objects with a  $\Delta v^{\text{SH}}$  between 4.5 and  $5.5 \text{ km s}^{-1}$  (i.e., 63 MANOS objects have a  $\Delta v^{\text{SH}} > 5.5 \text{ km s}^{-1}$ ). Figure 2 shows MANOS objects reported in this work.

The Shoemaker & Helin (1978) formalism is only a first approximation to estimate if an object is truly spacecraft accessible. In fact, full orbital integrations are needed to calculate accurate  $\Delta v$ . The Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) performs more accurate  $\Delta v^{\text{NHATS}}$  calculations that take into account specific launch windows, and the duration of the mission.<sup>12</sup> Several MANOS objects are listed on the NHATS webpage. For example, 2014 UV<sub>210</sub> with a  $\Delta v^{\text{SH}}$  of  $3.93 \text{ km s}^{-1}$  using Shoemaker & Helin (1978), has a  $\Delta v^{\text{NHATS}}$  of  $5.902 \text{ km s}^{-1}$  according to NHATS.

The cut-off for NHATS is for a  $\Delta v^{\text{NHATS}}$  of  $12 \text{ km s}^{-1}$ . A total of 33 MANOS objects have a  $\Delta v^{\text{NHATS}} \leq 12 \text{ km s}^{-1}$  and are mission accessible according to NHATS two calculations: 5 Aten, 9 Amor, and 19 Apollo (Figure 2 and Table 2). We report complete light curve for 30 of these 33 objects (two have flat light curves, one with partial light curve), and 26 of them are characterized with light curve and spectra in the visible (five of them have also infrared spectra). Abell et al. (2009) consider a rotational period of 1 hr as a practical limit independent of the nature of the future mission (robotic or human). Only seven of the objects presented here meet the NHATS dynamical criteria and the 1 hr rotation limit (Table 2).

## 3. OBSERVATIONS AND DATA REDUCTION

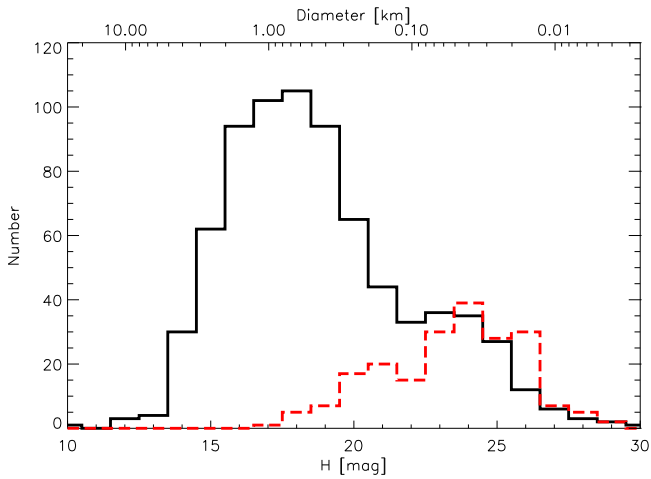
### 3.1. Telescope Resources

Here, we present photometric results for 86 MANOS targets, representing a statistically significant subset of the overall MANOS sample. In approximately two years, a total of 207 objects have been observed for light curves. The remaining objects as well as future observations will be published at a later time. The data presented here were obtained with the 4.3 m Lowell Discovery Channel Telescope (DCT), the 4.1 m SOAR telescope, the 4 m Nicholas U. Mayall Telescope, the 2.1 m at Kitt Peak Observatory, the 1.8 m Perkins telescope, the 1.5 m Sierra Nevada Observatory (OSN), and the 1.3 m SMARTS telescope between 2013 August and 2015 October.

The DCT is forty miles southeast of Flagstaff at the Happy Jack site (Arizona, USA). Images were obtained using the

<sup>11</sup> [http://echo.jpl.nasa.gov/~lance/delta\\_v/delta\\_v.rendezvous.html](http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html)

<sup>12</sup> For more details, see <http://neo.jpl.nasa.gov/nhats/>.



**Figure 1.** Number of objects vs. absolute magnitude: absolute magnitude ( $H$ ) distribution of all NEOs with previously obtained light curve (continuous black line: data from Warner et al. 2009 on 2015 July), and MANOS objects observed for light curves over  $\sim 2$  years (discontinuous red line). Here we report results for 86 MANOS targets. Our full sample will be published at a later date. Diameter was computed assuming an albedo of 0.2.

Large Monolithic Imager (LMI), which is a  $6144 \times 6160$  CCD (Levine et al. 2012). The total field of view is  $12'5 \times 12'5$  with a plate scale of  $0''.12 \text{ pixel}^{-1}$  (unbinned). Images were obtained using the  $3 \times 3$  or  $2 \times 2$  binning modes. Observations were carried out in situ.

The SOAR telescope is located on Cerro Pachón, Chile. Images were obtained using the Goodman High Throughput Spectrograph (Goodman-HTS) instrument in its imaging mode. The instrument consists of a  $4096 \times 4096$  Fairchild CCD, with a  $7'2$  diameter field of view (circular field of view) and a plate scale of  $0''.15 \text{ pixel}^{-1}$ . Images were obtained using the  $2 \times 2$  binning mode. Observations were conducted remotely.

The Mayall telescope is a 4 m telescope located at the Kitt Peak National Observatory (Tucson, Arizona, USA). The NOAO CCD Mosaic-1.1 is a wide field imager composed of an array of eight CCD chips. The field of view is  $36' \times 36'$ , and the plate scale is  $0''.26 \text{ pixel}^{-1}$ . Observations were performed remotely.

The 2.1 m at Kitt Peak Observatory was operated with the STA3  $2k \times 4k$  CCD, which has a plate scale of  $0''.305 \text{ pixel}^{-1}$  and a field of view of  $10'2 \times 6'6$ . The instrument was binned  $2 \times 2$  and the observations were conducted in situ.

The Perkins 72" telescope is located at the Anderson Mesa station at Lowell Observatory (Flagstaff, Arizona, USA). We used the PRISM (Perkins ReImaging System) instrument, a  $2 \times 2k$  Fairchild CCD. The PRISM plate scale is  $0''.39 \text{ pixel}^{-1}$  for a field of view of  $13' \times 13'$ . Observations were performed in situ.

The 1.5 m telescope located at the OSN at Loma de Dilar in the National Park of Sierra Nevada (Granada, Spain) was operated in situ. Observations were carried out with a  $2k \times 2k$  CCD, with a total field of view of  $7'8 \times 7'8$ . We used  $2 \times 2$  binning mode, resulting in an effective plate scale of  $0''.46 \text{ pixel}^{-1}$ .

The 1.3 m SMARTS telescope is located at the Cerro Tololo Inter-American Observatory (Coquimbo region, Chile). This

telescope is equipped with a camera called ANDICAM (A Novel Dual Imaging CAMera). ANDICAM is a Fairchild  $2048 \times 2048$  CCD. The pixel scale is  $0''.371 \text{ pixel}^{-1}$ , and the field of view is  $6' \times 6'$ . Observations were carried out in queue mode.

### 3.2. Observing Strategy, Data Reduction, and Analysis

Exposure times were chosen based on two competing factors: (i) the exposure had to be long enough to achieve sufficient signal-to-noise ratio ( $S/N$ ) to resolve typical light curve variability (i.e.,  $S/N > 20$ ); and (ii) the exposure had to be short enough to avoid significant elongation of sources due to the non-sidereal motion of the target. We always elected to track the telescopes at sidereal rates, mainly to avoid significant elongation of the sources, and because we can use the same reference stars for the photometry. Exposure times between 1 and 200 s were used according to the sky motion and brightness of the object, and the telescope aperture. It is important to point out that the use of long exposure times is a problem in case of fast or ultra-rapid rotators. In fact, if the exposure time (+ the read-out time) are consistent or longer than the rotational period of the object, we will not be able to detect the fast rotation of the object and the light curve will be flat. Here, we report several flat light curves. Most of the objects are large and we are not expecting them to be fast rotators. However, several objects are small and are potential fast rotators whose rotational period gets undetected because of the too long exposure time used (three objects reported here: 2014 YD<sub>42</sub>, 2015 EQ, and 2015 HS<sub>1</sub>). This topic will be studied in more detail in a future work.

Broad-band photometric filters were chosen to maximize  $S/N$ , to minimize fringing at long wavelengths, and to choose the band-pass to sky brightness conditions dictated by lunar phase. Observations at the OSN were performed without a filter. We used the V, R, open and  $r'$  filters at SOAR. With the DCT and the 1.8 m Perkins we used broad VR filters. The broad wh-filter (transmission from  $0.4\text{--}0.9 \mu\text{m}$ ) was used at Kitt Peak. Since these observations focused on deriving relative photometric variations, the use of multiple filters and unfiltered images without absolute calibration did not affect our science goals.

Approximately 45% of sub-km NEOs have a rotational period  $< 3$  hr, whereas  $\sim 88\%$  of sub-100 m NEOs have period less than 3 hr (Warner et al. 2009). A MANOS goal is to characterize small objects; thus we dedicated observing blocks of  $\sim 3$  hr per object. With this strategy we were generally able to observe at least one full rotation, although this strategy does bias against the detection of slow rotators.

As our strategy is designed for rapid response and building population statistics, we cannot and do not spend several nights per target. Therefore, shape modeling, which requires several epochs of data, is not feasible. However, we report three objects with two light curves obtained at different epochs, with the intent that these data will prove useful for future shape modeling efforts.

During each observing night, a series of bias and flat fields (dome and/or twilight flats) were obtained to correct the images. We created a median bias and median flatfield for each night. Target images were bias subtracted and flatfielded.

**Table 1**  
Summary of Observations<sup>a</sup>

Object	Date	$N_{im}$	$r_h$ (AU)	$\Delta$ (AU)	$\alpha$ ( $^\circ$ )	Filter	Tel.	Rot. Per. (hr)	$\Delta m$ (mag)	$\varphi_0$ (JD) [2450000+]	$H$ (mag)	Diameter (m)	Dyn. class	$\Delta v^{SH}$ (km s $^{-1}$ )
<i>Full light curve:</i>														
<i>Symmetric light curve:</i>														
2014 GQ <sub>17</sub>	2014/04/10	233	1.019	0.020	28.12–28.49	VR	DCT	0.0217	0.08 $\pm$ 0.01	6757.64339	27.1	11	Aten	6.86
2014 MD <sub>6</sub>	2014/08/20	79	1.032	0.108	76.20–76.16	VR	DCT	1.63	0.17 $\pm$ 0.03	6889.91573	21.5	148	Amor	6.12
2014 VG <sub>2</sub>	2014/11/26	155	1.055	0.105	47.10–47.18	VR	DCT	0.0385	0.08 $\pm$ 0.01	6987.66738	22.6	89	Apollo	5.15
2014 WR <sub>6</sub>	2014/11/26	207	1.027	0.046	27.70–27.97	VR	DCT	0.1416	0.67 $\pm$ 0.02	6987.57843	25.3	25	Amor	5.78
2015 DS	2015/03/10	158	1.019	0.044	51.92–51.95	r'	SOAR	1.00	0.54 $\pm$ 0.02	7091.53468	24.9	31	Amor	4.51
2015 EK	2015/03/11	130	1.002–1.004	0.013–0.015	46.03–42.09	VR	DCT	0.0737	0.17 $\pm$ 0.02	7092.63387	26.3	16	Apollo	5.57
2015 LQ <sub>21</sub>	2015/06/21	85	1.042	0.035	42.29–42.23	VR	DCT	0.69	0.24 $\pm$ 0.02	7194.94385	24.5	37	Amor	6.07
<i>Asymmetric light curve:</i>														
2005 ES <sub>70</sub>	2015/03/10	115	1.054	0.066	21.34–21.07	r'	SOAR	1.69	0.55 $\pm$ 0.02	7091.82669	23.8	51	Aten	12.22
2008 KZ <sub>5</sub>	2013/09/27	200	1.042	0.109	65.75–65.65	V	CTIO	1.92	0.11 $\pm$ 0.04	6563.68999	20.1	283	Amor	5.74
2010 AF <sub>30</sub>	2013/08/02	68	1.114	0.113	27.13–27.03	V	SOAR	2.6	0.06 $\pm$ 0.01	6507.67354	21.7	135	Apollo	5.63
2013 BO <sub>76</sub>	08/28, 08/31, 09/01/2013	135	1.232–1.265	0.225–0.259	0.84–0.10	V	CTIO	5.03	0.26 $\pm$ 0.04	6533.71073	20.4	247	Apollo	6.29
2013 NJ	2014/01/08	55	1.159	0.192–0.193	22.02–22.04	VR	DCT	2.02	0.06 $\pm$ 0.02	6665.87196	21.9	123	Apollo	4.87
2013 NX <sup>b</sup>	2015/03/14	53	1.076	0.166	56.44–56.38	wh	KP4	0.1529	0.84 $\pm$ 0.02	7095.96172	22.0	118	Apollo	5.49
2013 NX <sup>b</sup>	2013/08/02	55	1.085	0.084	31.66–31.88	r'	SOAR	0.1527	0.89 $\pm$ 0.02	6507.49100	...	...	...	...
2013 TG <sub>6</sub>	2013/10/09	127	1.023	0.247	73.76–73.71	V	SOAR	0.0631	0.18 $\pm$ 0.02	6575.63856	26.6	14	Aten	5.1
2013 WA <sub>44</sub>	2014/01/08	63	1.143	0.213	37.59–37.67	VR	DCT	0.35	0.23 $\pm$ 0.04	6665.75749	23.7	54	Amor	4.17
2014 DH <sub>10</sub>	2014/03/26	130	1.089	0.092–0.093	7.83–7.85	R	SOAR	0.2662	0.74 $\pm$ 0.02	6742.63103	25.8	20	Amor	5.37
2014 EK <sub>24</sub> <sup>b</sup>	2014/03/25	76	1.057	0.068	27.73–27.78	V	CTIO	0.0998	1.26 $\pm$ 0.01	6741.74154	23.2	68	Apollo	4.88
2014 EK <sub>24</sub> <sup>b</sup>	2015/02/11	432	1.011	0.046	57.38–57.19	VR	DCT	0.0996	0.56 $\pm$ 0.02	7064.93072	...	...	...	...
2014 FP <sub>47</sub>	2014/04/10	183	1.153–1.152	0.157	14.90–15.07	VR	DCT	0.44	0.17 $\pm$ 0.01	6757.75387	22.3	103	Apollo	5.2
2014 KQ <sub>84</sub>	2014/05/31	108	1.036	0.024	20.53–20.28	r'	SOAR	0.0938	0.37 $\pm$ 0.03	6809.76403	26.7	13	Amor	4.89
2014 PR <sub>62</sub>	2014/09/10	49	1.1800	0.189	21.80–21.83	V	CTIO	0.0947	0.28 $\pm$ 0.02	6910.66708	20.6	225	Amor	6.78
2014 RC <sup>b</sup>								0.00439	0.01 $\pm$ 0.01		26.8	12	Apollo	5.75
2014 UV <sub>210</sub>	2014/12/08	99	2.158	1.184	5.27–5.32	Cle	OSN	0.5559	0.91 $\pm$ 0.02	7000.32630	26.7	13	Amor	3.93
2014 UY	2014/12/03	116	0.995	0.036	73.11–73.24	r'	SOAR	0.0658	0.87 $\pm$ 0.03	6995.79968	25.3	25	Apollo	4.43
2014 WB <sub>366</sub>	2014/12/17	78	1.024	0.045	26.77–26.78	VR	DCT	0.0238	0.46 $\pm$ 0.02	7008.70556	24.8	32	Apollo	5.19
2014 WC <sub>201</sub>	2014/11/28	89	1.010	0.024	13.48–13.51	VR	DCT	0.95	0.38 $\pm$ 0.02	6990.01152	26.1	17	Apollo	6.28
2014 YD	2015/01/13	151	0.996	0.044	72.66–72.76	r'	SOAR	2.12	0.20 $\pm$ 0.02	7035.77312	24.3	41	Apollo	3.98
2015 AZ <sub>43</sub> <sup>b</sup>	2015/02/10	333	1.005–1.004	0.0219	51.36–51.44	wh	KP4	0.5969	0.39 $\pm$ 0.02	7063.93078	23.4	62	Apollo	5.65
2015 BF <sub>511</sub>	2015/02/10	263	1.020	0.041	34.98–35.13	wh	KP4	0.576	0.52 $\pm$ 0.02	7063.83662	24.8	32	Apollo	4.92
2015 BG <sub>92</sub>	2015/01/29	175	1.013	0.029	14.21–13.98	VR	DCT	0.179	0.36 $\pm$ 0.02	7051.89156	25.0	29	Apollo	5.24
2015 BM <sub>510</sub>	2015/02/05	193	1.011	0.036–0.037	45.24–45.56	r'	SOAR	0.806	0.39 $\pm$ 0.04	7059.52984	25.1	28	Aten	4.79
2015 CB <sub>1</sub>	2015/02/11	67	1.005	0.027	48.65–48.76	VR	DCT	0.0589	0.36 $\pm$ 0.02	7064.85546	25.5	23	Amor	5.69
2015 CD <sub>1</sub>	2015/02/11	68	0.996	0.012	38.7	VR	DCT	0.0167	0.28 $\pm$ 0.02	7064.79444	28.2	6	Apollo	4.92
2015 CM	2015/02/11	62	1.009	0.023	16.77–16.85	VR	DCT	0.02678	0.53 $\pm$ 0.02	7064.81885	26.2	17	Amor	6.27
2015 CS	2015/02/11	72	1.008	0.022	19.22–19.17	VR	DCT	0.2433	0.79 $\pm$ 0.01	7064.83603	26.3	16	Apollo	5.81
2015 CW <sub>12</sub>	2015/03/11	183	1.067	0.104	42.48–42.56	VR	DCT	2.01	0.20 $\pm$ 0.04	7092.94971	23.0	74	Amor	5.2
2015 DT	2015/02/22	120	1.080–1.079	0.093–0.092	11.33–11.28	V	CTIO	0.0426	0.20 $\pm$ 0.04	7075.66190	22.9	78	Apollo	6.68
2015 DU	2015/03/10	110	1.017	0.026	20.64–20.68	r'	SOAR	0.076	0.05 $\pm$ 0.02	7091.63277	26.6	14	Amor	3.97
2015 EG	2015/03/10	62	1.022	0.030	9.45–9.49	r'	SOAR	1.29	0.29 $\pm$ 0.02	7091.79723	25.7	21	Aten	7.96



**Table 1**  
(Continued)

Object	Date	$N_{im}$	$r_h$ (AU)	$\Delta$ (AU)	$\alpha$ ( $^\circ$ )	Filter	Tel.	Rot. Per. (hr)	$\Delta m$ (mag)	$\varphi_0$ (JD) [2450000+]	$H$ (mag)	Diameter (m)	Dyn. class	$\Delta v^{SH}$ (km s $^{-1}$ )
2015 EO	2015/03/14	110	1.007–1.006	0.014–0.013	23.01–23.31	wh	KP4	0.073	$0.39 \pm 0.02$	7095.67617	26.8	12	Apollo	6.76
2015 FP	2015/03/25	45	1.025	0.028	4.17–4.18	VR	DCT	0.1872	$0.53 \pm 0.03$	7106.86738	25.2	27	Amor	5.51
2015 HM <sub>10</sub>	2015/06/29	79	1.011	0.042	96.10–96.25	r'	SOAR	0.3763	$1.29 \pm 0.02$	7202.48903	23.6	56	Amor	6.3
2015 HR <sub>1</sub>	2015/04/29	60	1.138	0.132	5.47–5.48	r'	SOAR	0.0467	$0.60 \pm 0.20$	7141.64653	24.6	35	Amor	6.53
2015 SO <sub>2</sub>	2015/09/25	188	1.024	0.041	58.07–58.12	VR	DCT	0.58	$1.65 \pm 0.02$	7290.85686	23.9	49	Aten	6.01
2015 SO <sub>2</sub>	2015/09/28	64	1.019	0.038	62.7	r'	SOAR	...	...	7293.80409	...	...	...	...
2015 SU	2015/09/25	94	1.040	0.039	18.98–19.11	VR	DCT	0.0127	$0.20 \pm 0.03$	7290.74336	25.4	24	Amor	6.47
2015 SU <sub>16</sub>	2015/09/25	79	1.048	0.053	30.81–30.74	VR	DCT	0.2052	$0.24 \pm 0.03$	7290.91196	24.7	34	Amor	6.73
2015 SV <sub>6</sub> <sup>b</sup>	2015/09/25	40	1.009–1.008	0.007	42.47–43.06	VR	DCT	0.00490	$0.74 \pm 0.03$	7290.61019	27.7	8	Apollo	7.56
2015 SZ <sub>2</sub>	2015/09/25	99	1.020	0.019–0.018	19.63	VR	DCT	0.0384	$0.29 \pm 0.03$	7290.62516	25.2	27	Apollo	4.91
<i>Complex light curve:</i>														
2013 WS <sub>43</sub>	2014/01/08	281	0.999	0.0606	72.97–73.20	VR	DCT	0.0988	$0.39 \pm 0.01$	6665.94480	22.8	81	Apollo	5.51
2015 AK <sub>45</sub>	2015/01/28	130	0.992	0.015	58.23–58.92	VR	DCT	0.0258	$0.24 \pm 0.02$	7050.99769	26.4	15	Apollo	6.59
2015 EP	2015/03/11	305	1.012	0.020	18.78–18.46	VR	DCT	0.0381	$0.10 \pm 0.02$	7092.66571	25.9	19	Amor	5.55
2015 FG <sub>36</sub>	2015/04/04	109	1.032	0.064	58.36–58.46	r'	SOAR	2.32	$0.59 \pm 0.02$	7116.60147	23.8	51	Apollo	4.67
2015 JF	2015/05/12	124	1.035	0.026	11.38	VR	DCT	0.1897	$0.33 \pm 0.03$	7154.74071	26.3	16	Apollo	5.21
2015 OM <sub>21</sub>	2015/07/29	209	1.092	0.110	43.90–43.93	VR	DCT	0.4084	$0.55 \pm 0.02$	7232.90854	22.4	98	Amor	6.51
2015 OV	2015/08/18	143	1.055	0.079	55.69–55.76	VR	DCT	1.17	$0.38 \pm 0.02$	7252.92100	23.4	62	Apollo	5.18
2015 QB	2015/08/18	174	1.068–1.069	0.061	22.60–22.61	VR	DCT	0.0327	$0.11 \pm 0.03$	7252.79872	24.3	41	Amor	5.4
2015 SW <sub>6</sub>	2015/09/25	64	1.073	0.071	11.77–11.79	VR	DCT	0.0752	$0.32 \pm 0.03$	7290.71933	24.5	37	Apollo	6.50
2015 TC <sub>25</sub> <sup>b</sup>	2015/10/12							0.03715	$0.40 \pm 0.03$		29.6	3	Apollo	4.73
<i>Partially constrained:</i>														
2002 DU <sub>3</sub>	2013/10/27	70	1.321–1.322	0.369–0.372	23.6–23.9	r'	KP2	4.4	$0.24 \pm 0.02$	6593.84555	20.7	215	Apollo	5.63
2015 CO	2015/02/10	220	1.039	0.053	7.15–7.24	VR	DCT	4.9	$0.16 \pm 0.02$	7063.80413	26.2	17	Amor	5.09
2015 DZ <sub>198</sub>	2015/03/11	51	1.099–1.100	0.108	11.19–11.12	VR	DCT	4.72	$0.39 \pm 0.03$	7092.82531	24.6	35	Apollo	5.99
<i>Partial light curve:</i>														
2006 FJ <sub>9</sub>	2013/10/09	83	1.469	0.730–0.731	37.89	V	SOAR	>2	>0.2	6575.49351	19.3	410	Amor	5.85
2010 XZ <sub>67</sub>	2014/01/08	148	1.059–1.060	0.081	18.72–18.84	VR	DCT	>2	>0.3	6665.66272	19.7	341	Amor	6.81
2011 BN <sub>24</sub>	2013/09/13	48	1.344	0.340	4.35–4.34	V	SOAR	>1.5	>0.7	6552.57891	20.9	196	Apollo	5.49
2014 BR <sub>43</sub>	2014/04/18	112	1.285	0.302	23.57–23.59	Cle	SOAR	>2	>1.2	6824.45356	21.5	148	Amor	6.09
2014 CJ <sub>14</sub>	2014/03/25	92	1.173	0.229–0.230	36.20–36.29	VR	DCT	>2.5	>0.04	6741.66115	21.0	187	Amor	6.17
2014 FA <sub>44</sub>	2014/04/18	179	1.069	0.069–0.068	17.85–17.92	Cle	SOAR	>2	>1	6765.59264	24.8	32	Amor	4.49
2014 FN <sub>33</sub>	2014/04/10	177	1.200	0.231–0.230	27.83–27.88	VR	DCT	>2	>0.15	6757.90190	21.0	187	Amor	5.52
2014 HQ <sub>124</sub> <sup>c</sup>	2014/05/25	47	1.042–1.041	0.112–0.111	72.21–72.23	V	CTIO	>2.5	>0.5	6802.82845	18.9	493	Aten	12.29
2014 NA <sub>64</sub>	2014/07/28	219	1.204	0.193	10.44–10.46	V	CTIO	>1.5	>0.3	6870.72426	19.8	325	Amor	6.85
2015 HA <sub>1</sub>	2015/04/28	89	1.119	0.166	44.36–44.29	VR	Perkins	>1.5	>0.1	7140.86188	21.2	171	Aten	8.96
2015 SY	2015/09/25	171	1.079–1.080	0.077	4.98–4.82	VR	DCT	>0.9	>0.3	7290.94053	23.1	71	Aten	10.59
2015 SZ	2015/09/25	102	1.082	0.085–0.084	19.98–19.96	VR	DCT	>1	>0.1	7290.76432	23.3	65	Amor	5.82
<i>Flat light curve:</i>														
1994 CJ <sub>1</sub>	2014/07/20	159	1.131	0.140–0.141	33.08–33.02	r'	SOAR	...	...	6859.48559	21.4	155	Amor	4.7
2004 BZ <sub>74</sub>	2014/05/23	45	1.486	0.593	29.40–29.44	V	CTIO	...	...	6800.55622	18.1	712	Apollo	10.77

**Table 1**  
(Continued)

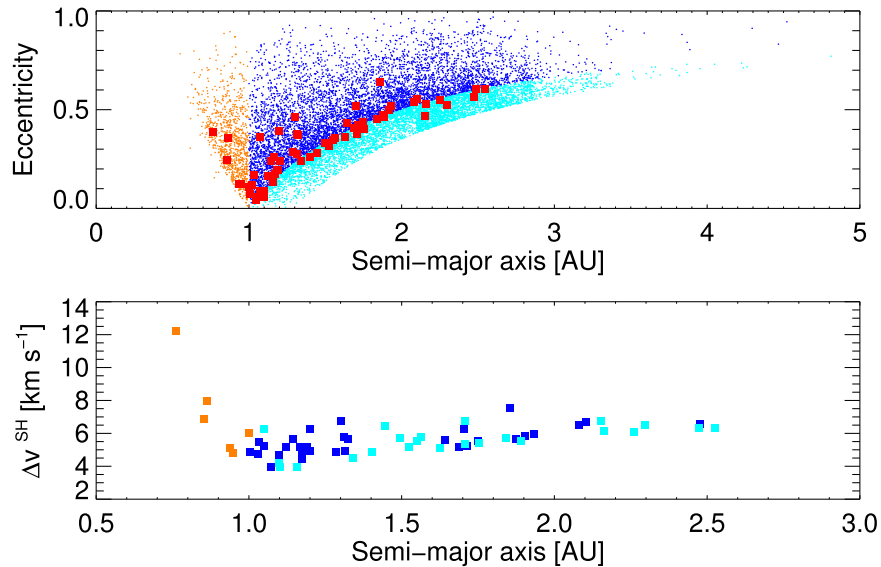
Object	Date	$N_{im}$	$r_h$ (AU)	$\Delta$ (AU)	$\alpha$ ( $^\circ$ )	Filter	Tel.	Rot. Per. (hr)	$\Delta m$ (mag)	$\varphi_0$ (JD) [2450000+]	$H$ (mag)	Diameter (m)	Dyn. class	$\Delta v^{SH}$ (km s $^{-1}$ )
2005 RO <sub>33</sub>	2013/10/26	100	1.270	0.314	24.93–24.85	V	CTIO	...	...	6592.60443	20.1	283	Amor	6.30
2007 CN <sub>26</sub>	2013/09/17	160	1.064	0.083–0.084	43.43–43.30	V	CTIO	...	...	6552.69735	21.1	179	Apollo	5.09
2008 TZ <sub>3</sub>	2014/04/10	75	1.122	0.158	37.82–37.86	V	CTIO	...	...	6757.73932	20.4	247	Apollo	5.53
2011 ST <sub>232</sub>	2014/08/03	141	1.156	0.145	11.04–11.03	V	CTIO	...	...	6872.72034	21.3	163	Amor	6.38
2011 WU <sub>95</sub>	2013/10/25	140	1.317–1.318	0.335	13.17–13.05	V	CTIO	...	...	6591.64622	19.4	391	Apollo	5.54
2012 XQ <sub>93</sub>	2014/08/10	175	1.109	0.153	48.33–48.54	r'	SOAR	...	...	6879.46564	21.7	135	Apollo	5.9
2013 YZ <sub>37</sub>	2014/02/11	200	1.203	0.225	14.7–14.6	V	CTIO	...	...	6700.66054	19.8	325	Amor	6.56
2014 CP <sub>13</sub>	2014/02/22	175	1.054	0.098	46.40–46.55	r'	SOAR	...	...	6710.52583	18.5	592	Amor	5.7
2014 SM <sub>143</sub>	2014/10/08	114	1.080	0.134–0.133	50.19–50.24	V	CTIO	...	...	6938.69803	20.3	258	Apollo	9.9
2014 YD <sub>42</sub>	2015/01/13	137	1.267	0.284–0.285	3.36–3.46	r'	SOAR	...	...	7035.66012	22.2	107	Apollo	6.83
2015 EQ	2015/03/14	52	0.999	0.013	65.63–65.77	wh	KP4	...	...	7095.66094	26.1	17	Aten	12.87
2015 HS <sub>1</sub>	2015/04/29	77	1.104	0.098	4.50–4.51	r'	SOAR	...	...	7141.58920	24.7	34	Amor	6.15

**Notes.**

<sup>a</sup> Dates (UT-dates, format YYYY/MM/DD), heliocentric ( $r_h$ ), and geocentric ( $\Delta$ ) distances and phase angle ( $\alpha$ ) of the observations are reported. The number of images ( $N_{im}$ ), photometric filter, and the telescope (Tel.) are indicated for each entry. See text for facility details. We present the preferred rotational period (Rot. per. in hour), the peak-to-peak light curve amplitude ( $\Delta m$  in magnitude, without phase angle correction), and the Julian date ( $\varphi_0$ ) corresponding to phase zero. The Julian date is not light time corrected. We also indicate the absolute magnitude ( $H$ ) from the Minor Planet Center (MPC) database, and a crude estimate of the object diameter assuming an albedo of 0.20. Our data set is classified into three main categories: (i) object with a full light curve, (ii) object with only a partial light curve and (iii) object with a flat light curve (i.e., no significant variability during our observing).

<sup>b</sup> Objects whose study will be presented in details in future works. Observing circumstances are not reported here.

<sup>c</sup> Contact binary (Benner et al. 2014).



**Figure 2.** Eccentricity and  $\Delta v^{SH}$  vs. semimajor axis. All known NEOs (data from the MPC webpage) are plotted. Different colors correspond to different dynamical classes: Aten in orange, Apollo in blue, and Amor in cyan. MANOS objects with a rotational period and light curve amplitude are plotted (red squares upper plot). MANOS targets are plotted in the lower plot according to their dynamical class (Aten in orange, Apollo in blue, and Amor in cyan). The  $\Delta v^{SH}$  values are computed using the Shoemaker & Helin (1978) formalism. MANOS observed five objects with a  $\Delta v^{SH}$  lower than  $4 \text{ km s}^{-1}$ , four objects with a  $\Delta v^{SH}$  between 4 and  $4.5 \text{ km s}^{-1}$ , and 23 objects with a  $\Delta v^{SH}$  between 4.5 and  $5.5 \text{ km s}^{-1}$ .

Relative photometry using up to 30 reference stars was carried out using Daophot routines (Stetson 1987). Time-series photometry of each target was inspected for periodicity by means of the Lomb technique (Lomb 1976) as implemented in Press et al. (1992). This method is a modified version of the Fourier spectral analysis. The main difference with the Fourier spectral analysis is the fact that this method takes into account irregularly spaced data. This method gives a weight to each data point instead of considering an interval time. We also verified our results by using the CLEAN (Foster 1995), and the Phase Dispersion Minimization (Stellingwerf 1978) methods.

When a possible rotational period is identified, it is useful to know how confident that estimation is. The confidence level is given by:

$$P(>z) = 1 - (1 - e^{-z})^M \quad (1)$$

where  $M$  is the number of independent frequencies, and  $z$  is the spectral power (Scargle 1982; Press et al. 1992). Lomb periodograms with confidence levels of 90%, 99%, and 99.9% are plotted in Figures 8–17, see the Appendix. Only periodograms for objects with an estimated rotational period are plotted (i.e., periodograms of flat and partial light curves are not reported). We considered a large range of frequency up to 5000 cycles/day which allows us to test our data for short and long periodicities. Care has to be taken to interpret the peaks of the periodogram. For example, there are frequencies not randomly spaced in time such as the exposure time, the read-out time of the instrument, the duration of the observing block, the duration of the pointings, and the aliases of the main peak. These frequencies can be confounded with the main peak (the tallest peak) which corresponds to the rotation of the object. Rotational periods reported in Table 1 correspond to the

highest peak. Error bar for the rotational period is the width of the main peak.

#### 4. PHOTOMETRIC RESULTS

Light curves are plotted<sup>13</sup> in Figures 18–27, see the Appendix. For each light curve, a Fourier series is fit to the photometric data. The order of the fit depends on the light curve morphology. Light curves with a clear rotational signature are plotted over one full cycle (rotational phase from 0 to 1). Times for zero phase, without light time correction, corresponding to the beginning of the integration are reported in Table 1. Error bars for the measurements are not shown on the light curves for clarity. Typical error is about 0.02–0.03 mag, but it can be up to 0.04–0.05 mag in case of a faint and/or fast moving object. The full photometry with error bars will ultimately be made available in NASA’s Planetary Data System.

We report rotational periods and peak-to-peak amplitudes for 60 objects (~70% of our sample), lower limits for amplitude and periodicity for 13 objects (~15%), and 13 objects (~15%) that show flat light curves without any significant amplitude variation. All relevant geometric information about the objects at the dates of observation, the number of images and filters used are summarized in Table 1. We divide our sample into three groups: (i) *full light curve* with at least one full rotation or a significant fraction of one rotation to provide a clear period estimate, (ii) *partial light curve* with only an increasing or decreasing trend in apparent magnitude, resulting in no periodicity estimate, and (iii) *flat light curve* with no evident trend in magnitude and no periodicity estimate (Lacerda & Luu 2003).

<sup>13</sup> Alternative versions of the light curves are available online at <https://manosobs.wordpress.com/observations/neo-observing-log/>.

**Table 2**  
All 33 MANOS Targets with a  $\Delta_v^{\text{NHATS}}$  Lower than  $12 \text{ km s}^{-1}$

Object	$H$	Diameter	Rot. Period	Vis. Spectrum yes/no?	$\Delta_v^{\text{SH}}$	$\Delta_v^{\text{NHATS}}$	Next Optical Window
	(mag)	(m)	(hr)		( $\text{km s}^{-1}$ )	( $\text{km s}^{-1}$ )	
1994 CJ <sub>1</sub>	21.4	155	...	yes	4.7	11.928	05/2016
2007 CN <sub>26</sub>	21.1	179	...	yes	5.09	11.112	05/2016
2014 RC	26.8	12	0.00439	yes	5.75	11.610	...
2015 CD <sub>1</sub>	28.2	6	0.0167	no	4.92	7.651	...
2014 GQ <sub>17</sub>	27.1	11	0.0217	no	6.86	7.728	...
2015 CM	26.2	17	0.02678	no	6.27	7.760	...
2015 TC <sub>25</sub>	29.6	3	0.03715	yes	4.73	4.261	...
2015 SZ <sub>2</sub>	25.2	27	0.0384	no	4.91	7.401	...
2014 VG <sub>2</sub>	22.6	89	0.0385	yes	5.15	9.847	...
2013 TG <sub>6</sub>	26.6	14	0.0631	yes	5.1	5.577	...
2014 UY	25.3	25	0.0658	no	4.43	7.035	...
2015 DU	26.6	14	0.076	yes	3.97	5.278	...
2014 KQ <sub>84</sub>	26.7	13	0.0938	yes	4.89	9.734	...
2014 EK <sub>24</sub>	23.2	68	0.0998	yes	4.88	5.099	...
2013 NX	22.0	118	0.1529	yes	5.49	6.648	...
2015 BG <sub>92</sub>	25.0	29	0.179	yes	5.24	5.218	...
2013 WA <sub>43</sub>	23.7	54	0.35	yes	4.17	5.442	...
2014 FP <sub>47</sub>	22.3	103	0.44	yes	5.2	9.054	...
2014 UV <sub>210</sub>	26.7	13	0.5559	yes	3.93	5.902	...
2015 BF <sub>511</sub>	24.8	32	0.576	yes	4.92	9.752	...
2015 SO <sub>2</sub>	23.9	49	0.58	yes	6.01	6.034	...
2015 BM <sub>510</sub>	25.1	28	0.806	yes	4.79	5.638	...
2014 WC <sub>201</sub>	26.1	17	0.95	yes	6.28	11.835	...
2015 DS	24.9	31	1.00	no	4.51	9.648	01/2029
<b>2015 OV</b>	<b>23.4</b>	<b>62</b>	<b>1.17</b>	<b>yes</b>	<b>5.18</b>	<b>7.788</b>	03/2022
2015 EG	25.7	21	1.29	no	7.96	10.586	03/2019
2014 FA <sub>44</sub>	24.8	32	>2	yes	4.49	8.584	08/2017
<b>2013 NJ</b>	<b>21.9</b>	<b>123</b>	<b>2.02</b>	<b>yes</b>	<b>4.87</b>	<b>9.934</b>	05/2016
<b>2014 YD</b>	<b>24.3</b>	<b>41</b>	<b>2.12</b>	<b>yes</b>	<b>3.98</b>	<b>5.496</b>	10/2024
<b>2015 FG<sub>36</sub></b>	<b>23.8</b>	<b>51</b>	<b>2.32</b>	<b>yes</b>	<b>4.67</b>	<b>6.974</b>	11/2022
<b>2010 AF<sub>30</sub></b>	<b>21.7</b>	<b>135</b>	<b>2.6</b>	<b>yes</b>	<b>5.63</b>	<b>11.816</b>	07/2016
<b>2002 DU<sub>3</sub></b>	<b>20.7</b>	<b>215</b>	<b>4.4</b>	<b>yes</b>	<b>5.63</b>	<b>9.422</b>	09/2017
<b>2015 CO</b>	<b>26.2</b>	<b>17</b>	<b>4.9</b>	<b>yes</b>	<b>5.09</b>	<b>11.784</b>	none

**Note.** Parameter  $\Delta_v$  using Shoemaker & Helin (1978) ( $\Delta_v^{\text{SH}}$ ), and according NHATS are indicated in the last two columns ( $\Delta_v^{\text{NHATS}}$ ). The best candidates for future missions are indicated in bold/italic. The best candidates are objects with a long rotational period, a  $\Delta_v^{\text{NHATS}}$  lower than  $12 \text{ km s}^{-1}$ , and are objects fully characterized (light curves and spectra). The next opportunity to observe the best candidates for future missions is mentioned in the latest column (dates from NHATS webpage). We also included the next window for objects with  $P > 1 \text{ hr}$ , but without visible spectrum, as well as object with a potentially slow rotation or unknown rotation.

We highlight two ultra-fast rotators: 2014 RC, and 2015 SV<sub>6</sub>. 2014 RC (diameter of  $\sim 12 \text{ m}$ ) had a close encounter with the Earth in 2014 September. We obtained several light curves before and close to the fly-by and derived a rotational period of 15.8 s. Such fast rotation makes this object the fastest rotator known to date (Warner et al. 2009). MANOS also discovered the second fastest rotator, 2015 SV<sub>6</sub> (diameter of  $\sim 8 \text{ m}$ ) with a rotational period of about 18 s. A complete study of ultra-rapid rotators is in preparation (D. Polishook et al. 2016, in preparation). We include those rotation periods and light curve amplitudes in our ensemble analysis.

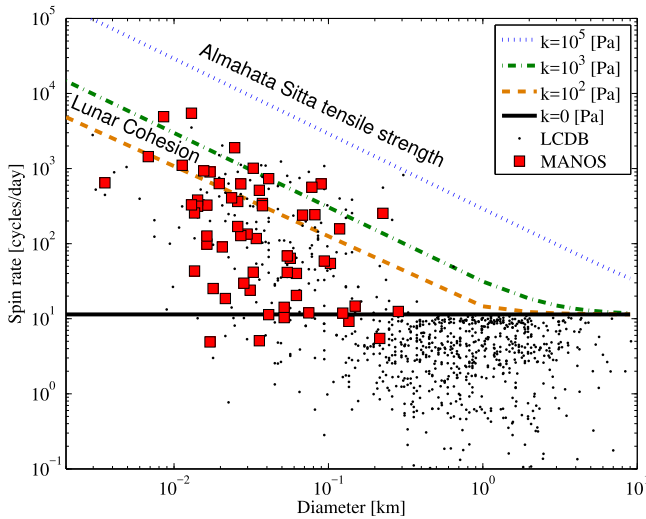
Several candidates for tumbling or non-principal axis rotation were identified and will be the topic of future work: 2015 LJ, 2015 CG, 2014 DJ<sub>80</sub>, and 2015 HB<sub>177</sub> (not reported in Table 1). Detailed studies of asteroids 2015 AZ<sub>43</sub> and 2015 TC<sub>25</sub> will be presented in T. Kwiatkowski et al. (2016, in

preparation), and V. Reddy et al. (2016, in preparation), respectively. The rotation periods and amplitudes of these objects are used here as part of our statistical analysis.

#### 4.1. Light curves

Photometric brightness variations are produced by several effects: (i) albedo variations across a body's surface, (ii) non-spherical shapes, and/or (iii) contact or eclipsing binary systems. Based on a lack of large scale albedo heterogeneity (i.e., detectable in unresolved images) among those NEOs visited by spacecraft (e.g., Clark et al. 2002; Saito et al. 2006) and the lack of binary systems at sizes below  $\sim 100 \text{ m}$  (Margot et al. 2002) the general expectation is that the photometric variability of our targets will be dominated by shape effects and thus the light curves will display two maxima and two minima with each rotation. We highlight that the changes of phase





**Figure 3.** Diameter–spin diagram of asteroids in the LCDB (dots) and the MANOS sample (squares). The lines represent boundaries for zero cohesion (solid line), 100 Pa (lower limit for lunar regolith; dashed line), 1000 Pa (higher limit for lunar regolith; dot-dash line), and  $10^5$  Pa (a lower limit for the tensile strength of the Almahata Sitta meteorite, dotted line). The lines were determined for bodies with  $\rho = 3.3 \text{ g cm}^{-3}$  and light curve amplitude of 0.5 mag, but it should be noted that the minimal cohesion is hardly sensitive to these parameters, and using  $\rho = 2 \text{ g cm}^{-3}$  and light curve amplitude of 0.1 mag give us similar results. The diameter was computed assuming an albedo of 0.2.

angle, and geocentric/heliocentric distances during the observing runs will introduce variations in the light curve. However, because we are only observing our targets during a couple of hours, such changes are minimal and are not affecting our light curves (see Table 1).

#### 4.1.1. Symmetric/Asymmetric Light curves

A symmetric light curve is one where both peaks reach the same relative magnitude. Only seven MANOS objects have symmetric light curves; most of the reported light curves are asymmetric with peaks that are not of the same amplitude. In our sample, the typical asymmetry is  $<0.15$  mag. However, five objects show larger variations: 2013 NX, 2015 BM<sub>510</sub>, 2015 HM<sub>10</sub>, 2015 SV<sub>6</sub>, and 2015 SO<sub>2</sub>.

1. 2013 NX was observed at two epochs in 2015 March and August with solar phase angles corresponding to  $\sim 56^\circ$  and  $\sim 31^\circ$  respectively. Light curve period and amplitude were derived from both epoch. Both light curves are asymmetric with peaks that differ in amplitude by about 0.2 mag (Figures 14 and 15).
2. 2015 BM<sub>510</sub> was observed with the 4 m SOAR telescope in 2015 February. The peaks differ in amplitude by 0.17 mag (Figure 18).
3. 2015 HM<sub>10</sub> was observed with the 4 m SOAR telescope in 2015 June. 2015 HM<sub>10</sub> shows an asymmetry of about 0.5 mag (Figure 20). 2015 HM<sub>10</sub> was observed with the Goldstone radar facility<sup>14</sup> during its close approach with Earth on the 2015 July 7 (Busch et al. 2015). A rotational period of  $\sim 0.4$  hr and elongated shape as suggested by our light curve data were confirmed by the radar observations.

4. 2015 SO<sub>2</sub> was observed on 2015 September 25 and September 28 with DCT and SOAR, respectively. Phase angles changed from  $\sim 58^\circ$  to  $\sim 63^\circ$  across those dates. A rotation period of 0.58 hr and light curve amplitude of 1.65 mag are consistent in both data sets. This object has the highest variability in our sample. The morphology of the light curve is also noteworthy (Figure 21). The first peak has a V-shape characteristic of a contact binary object, and an amplitude of about 0.9 mag compared to the first minimum. In contrast, the second minimum is U-shaped and is deeper by about 0.2 mag.
5. 2015 SV<sub>6</sub> has an absolute magnitude of 27.7 which corresponds to a diameter of 8 m assuming an albedo of 0.2. Observations of 2015 SV<sub>6</sub> were challenging because of the rapid sky motion of the object ( $\sim 155''/\text{min}$ ), and its apparent brightness (visual magnitude of  $\sim 18.8$ ). Due to this rapid sky motion, we used an exposure time of 1 s to avoid appreciable trailing of the object. With such short exposures we were sensitive to its very fast rotation of  $\sim 18$  s. The second interesting feature of this object is its light curve with a strong asymmetry of about 0.3 mag (D. Polishook et al. 2016, in preparation).

#### 4.1.2. Complex Shape

Ten MANOS targets display complex light curves that require higher order harmonics (i.e., more than two harmonics) in the fit: 2013 WS<sub>43</sub>, 2015 AK<sub>45</sub>, 2015 EP, 2015 FG<sub>36</sub>, 2015 JF, 2015 OM<sub>21</sub>, 2015 OV, 2015 QB, 2015 SW<sub>6</sub>, and 2015 TC<sub>25</sub>. Such curves can only be explained by complex shape and/or strong albedo variations. Such objects present an opportunity for future shape modeling pending the addition of multi-epoch observations. None of these objects has been observed by radar to provide any additional shape information.

#### 4.1.3. Partial and Flat Light curves

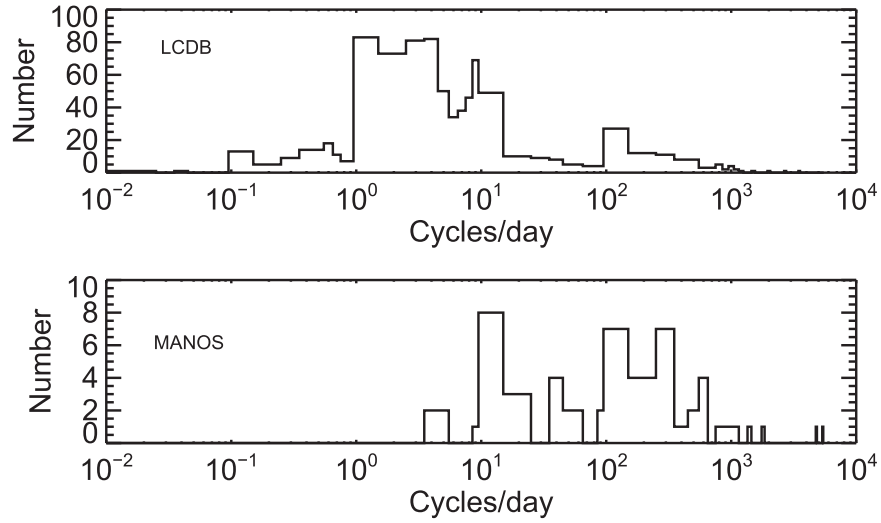
We also report partial light curves that show only a trend of increasing or decreasing magnitude. Because the data cover less than half of the object’s rotation, we are not able to derive a secure rotational period. Therefore, we report lower limits for these objects’ rotation periods and amplitudes. These results are only limits and are not used for our statistical study (see next section).

Some objects show no measurable photometric variations. In such a case, light curves are called flat light curves. Several causes can explain these light curves. The object may have (i) a long rotational period undetectable during our observing block, (ii) an almost pole-on orientation, (iii) a spherical shape, (iv) a very rapid rotation period comparable to or much less than the integration time per exposure. Additional observations would be needed to secure a rotational period for these objects.

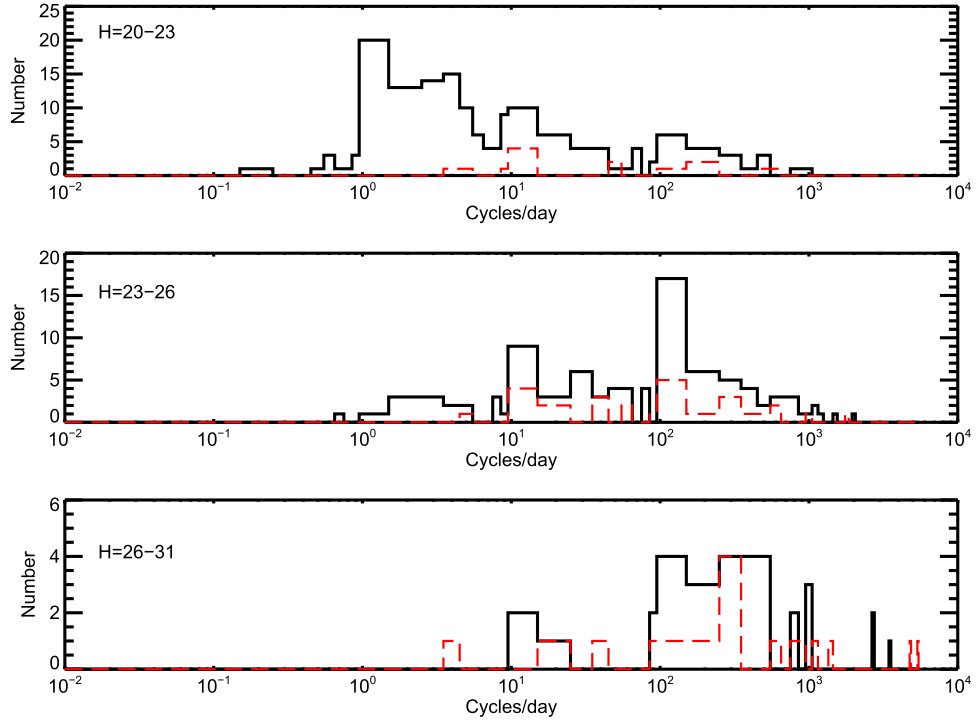
#### 4.1.4. Light curves with Mutual Eclipses

For binary systems, the light curve may present mutual eclipses due to the companion passing in front or behind the primary (Pravec et al. 2006). In our sample, the light curve of 2014 FA<sub>44</sub> may present some evidence of mutual eclipse (Figure 5). However, the light curve is incomplete and only more data at several epochs can confirm or not the presence of a companion.

<sup>14</sup> <http://echo.jpl.nasa.gov/asteroids/>



**Figure 4.** Rotational frequency distributions: we plotted all NEOs with a known rotational period reported in the light curve database (LCDB by Warner et al. 2009, upper plot), and MANOS results (lower plot). There are several biases in these data sets: (i) lack of objects with a rotational period longer than a day, and (ii) lack of ultra-rapid rotators.



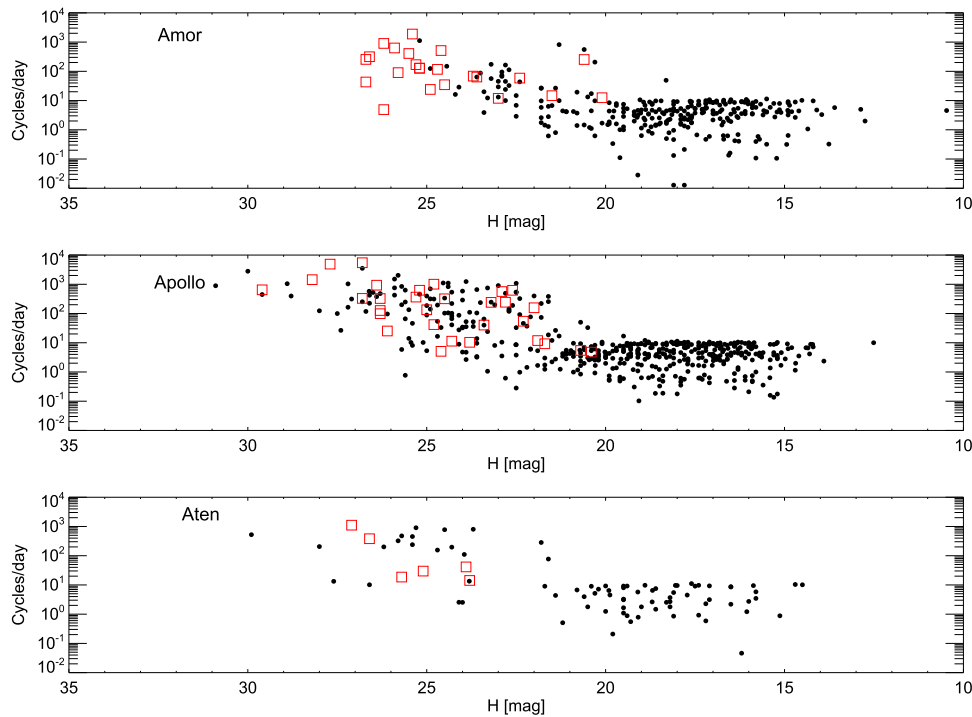
**Figure 5.** Number of objects vs. cycles/day: all NEOs with a known rotational period reported in the light curve database (black, Warner et al. 2009), and MANOS results (red) reported in this work are plotted. Objects have been sub-divided based on their absolute magnitude. For objects with  $H = 20-23$ , the mean rotational frequency is 71 cycles/day with a standard deviation of 171 cycles/day. For objects in the range  $H = 23-26$  ( $H = 26-31$ ), the mean frequency is 270 cycles/day (745 cycles/day) and the standard deviation is 380 cycles/day (1201 cycles/day).

## 5. DISCUSSION

### 5.1. Data set

We report a data set reduced and analyzed with the same methods that is well suited to statistical study. However, we have also used the light curve database by Warner et al. (2009) to increase the sample size (LCDB refers to the light curve

database hereafter). Merging our sample and the NEOs in the LCDB results in a sample of 906 objects (with rotational period and light curve amplitude). The LCDB uses a reliability code or quality rating to categorize light curves. This system is based on the work of Lagerkvist et al. (1989, p. 1162) who defined a reliability code from 1 (tentative result) to 4 (multiple apparition coverage, and pole position reported). Warner



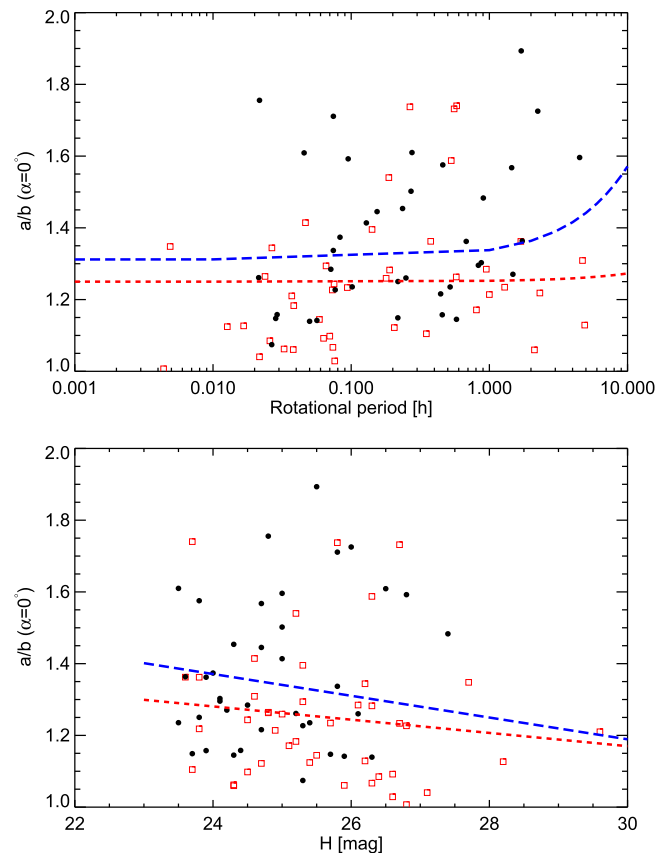
**Figure 6.** Rotational frequency vs. absolute magnitude( $H$ ): all NEOs with a known rotational period reported in the light curve database (black circles, Warner et al. 2009), and MANOS results (red squares) reported in this work are plotted. Objects have been sub-divided according to their dynamical class (i.e., Amor, Apollo, and Aten). MANOS is finding a significant number of small, fast rotating Amors which do not appear in the LCDB.

et al. (2009) suggested that a pole solution did not necessarily reflect the quality of the light curve, and thus removed the 4 code. Their ranking is: 1: result based on fragmentary light curve(s), may be completely wrong; 2: result based on less than full coverage, so period may be wrong by 30% or so; 3: secure result. MANOS light curves have a reliability code of 2 or 3 based on this classification.

Fifty-four objects ( $\approx 5\%$  of the LCDB) have a code of 1365 objects ( $\approx 37\%$ ) with a code of 2396 objects ( $\approx 40\%$ ) with a code of 3, and 180 objects ( $\approx 18\%$ ) with no code (only upper/lower limit on the rotational period and/or light curve amplitude). We do not make use of the Warner et al. (2009) + and - sub-division codes. Here, we consider nearly all objects independent of their reliability code. In fact, only 5% of the LCDB is composed of code values = 1, and thus their contribution to a statistical study is minor. Furthermore, Binzel et al. (1989, p. 416) pointed out several biases inherent to asteroid light curve literature that argue against removing low-quality data. They stressed that excluding poor-reliability objects results in overweighting objects with large amplitude and short rotational periods. The exception to our inclusion of the full LCDB are those objects with no reliability code. These objects do not have constraints on their light curve properties and cannot be included in our analysis.

### 5.2. Rotational Frequency Distribution

All asteroids with rotational periods reported in the literature are plotted in Figure 3 (LCDB by Warner et al. 2009). It has been shown that asteroids with sizes from a few hundred meters ( $\sim 200$  m) up to about 10 km show a spin deformation limit at  $\sim 2.2$  hr (Pravec et al. 2002, p. 113). In other words, this boundary is interpreted as a critical spin limit for rubble piles in the gravity regime. This limit disappears at



**Figure 7.** Axis ratio ( $a/b$ ) vs. rotational period and absolute magnitude ( $H$ ): MANOS (red squares) and Hatch & Wiegert (2015) data (black circles) are plotted. Axis ratio has been corrected for phase angle. Red (MANOS sample) and blue lines (MANOS+Hatch & Wiegert 2015 data sets) are linear fits. We find an insignificant correlation between axis ratio and rotational period in our sample.

diameters less than 200 m, suggesting that cohesion is important for the smallest asteroids. In fact, fast rotators cannot be held together by self-gravitation only (see Section 6 for more details).

MANOS objects are clustered in the left upper part of Figure 3. As already mentioned, our survey focuses on small NEOs and is sensitive to rotational periods from about 16 s to  $\sim 5$  hr. Approximately 50% of MANOS objects are spinning fast, in less than 5 minutes, which is expected in this size range. However, we highlight the “slow” rotation of 2015 CO. This object has an absolute magnitude of 26.2, so an approximate diameter of 17 m assuming an albedo of 0.2, and its rotational period is 4.9 hr. 2015 CO is the slowest rotator among objects smaller than 20 m. In Figure 3, asteroid diameters are reported assuming an albedo of 0.2. The diameter ( $D$ ) according to Pravec & Harris (2007), can be estimated by:

$$D = \frac{K}{\sqrt{p}} 10^{-0.2H} \quad (2)$$

where  $p$  is the geometric albedo, and  $H$  is the absolute magnitude. The constant  $K$  is:

$$K = 2 \text{ AU} \times 10^{-\frac{V_{\text{Sun}}}{5}} \quad (3)$$

where  $V_{\text{Sun}}$  is the visual magnitude of the Sun. Previous formulae are wavelength-dependent (Pravec & Harris 2007). The constant  $K$  is 1329 in the V-band and 1137 in the R-band. Absolute magnitudes in Table 1 are from the MPC<sup>15</sup> and have a typical error bar of 0.5 mag (Jurić et al. 2002; Pravec et al. 2012). Assuming the R-band (V-band), we derive a diameter of  $5 \pm 1$  m ( $4 \pm 1$  m) for an object with an absolute magnitude of  $H = 29 \pm 0.5$ . Geometric albedo is not available for all objects reported here, so we used a default value of 0.2. Within the error bars, the values are consistent, but one must keep in mind that such values are only rough estimates. Diameters for MANOS objects have been estimated assuming the R-band and are summarized in Table 1.

Figure 4 shows all NEOs reported in the LCDB and in the MANOS sample. There are several biases in these data sets. First bias is the lack of objects with a rotational period longer than a single day. Long rotation periods are difficult to determine due to alias effects and a requirement for long duration observations. Furthermore, null results or failed attempts to derive light curves are rarely published, which exacerbates this bias in the literature. Our observing strategy is not sensitive to slow rotation, and no objects with periods greater than about five hours are reported in our sample (see Section 3.2 for more details).

The second bias is against ultra-rapid rotators. From sampling theory (e.g., Nyquist 1928) it is known that periodic signals can only be reconstructed when sampled at a rate of at least twice the signal frequency. Larger aperture telescopes can generally employ shorter exposure times and thus are more sensitive to short rotational periods. For example, 2014 RC and 2015 SV<sub>6</sub> were observed with exposure times of  $\sim 1$ –2 s. As such, MANOS is sensitive to ultra-rapid rotation due to the regular use of 4 m aperture facilities, but that is generally not

the case for the majority of current asteroid light curve surveys. Our sensitivity to rotational periods  $< 1$  min is a novel benefit of the MANOS observing strategy, but we are still not able to probe periods comparable to observational cadences set by individual exposure times. In other words, we are not able to directly measure whether rotation periods  $\ll 10$  s exist among small NEOs.

### 5.2.1. Rotational Period versus Absolute Magnitude

In Figure 5, we plot NEOs with a rotational period available from the LCDB and the MANOS sample. This full sample has been divided according to the absolute magnitude ( $H$ ) of the objects:  $H = 20$ –23, 23–26 and a large bin for the smallest objects with  $H = 26$ –31. We only consider objects with an absolute magnitude higher than 20 (i.e., diameter smaller than  $\sim 300$  m assuming an albedo of 0.2) due to the MANOS focus on objects in this size range.

Despite the still limited MANOS sample, we note that our distribution is similar to the LCDB. In the size range  $H = 26$ –31, the distributions are sparse and it is difficult to distinguish an underlying distribution. For objects in the size range  $H = 20$ –23, the mean rotational frequency is 71 cycles/day with a standard deviation of 171 cycles/day. For objects in the range  $H = 23$ –26 ( $H = 26$ –31), the mean frequency is 270 cycles/day (745 cycles/day) and the standard deviation is 380 cycles/day (1201 cycles/day). Based on Figure 5, it is clear that rotational frequency distribution is size-dependent.

Binzel et al. (1989, p. 416) concluded that for asteroids with a diameter  $D > 125$  km, a Maxwellian distribution is able to fit the observed rotation rate distributions implying that their rotation rates may be determined by collisional evolution. However, for asteroids with a diameter  $D < 125$  km, there is an excess of slow rotators and their non-Maxwellian distributions suggests that their rotation rates are more strongly influenced by other process. An updated version of Binzel et al. (1989, p. 416) by Pravec et al. (2002, p. 113) showed that the rotational frequency distribution for large Main Belt asteroids (diameter larger than 40 km) can be fit by a Maxwellian distribution, but for very small NEOs, a Maxwellian fit is not able to match the observations. Based on our sample, we have an excess of slow (objects rotating in hours) and fast rotators (objects rotating in few minutes) which do not allow us to fit a Maxwellian distribution.

Several ideas have been proposed to explain the existence of these fast and slow rotators. The main processes to consider are radiation pressure effects (YORP), and gravitational interactions with planets during close encounters (Richardson et al. 1998; Pravec & Harris 2000; Rubincam 2000; Scheeres et al. 2000; Bottke et al. 2002). These effects can spin up or spin down objects, thus broadening the overall distribution of rotation rates. It is also thought that small objects are fragments of larger objects that have suffered a catastrophic collision (Morbidelli et al. 2002, pp. 409–422). This kind of collision produces fragments that are ejected and may have fast rotations. Tidal evolution in a binary system can slow down rotation rates, but there are no known binary systems among objects with a diameter  $< 100$  m.

<sup>15</sup> Absolute magnitudes are available at: <http://www.minorplanetcenter.net/iau/lists/MPLists.html>. Absolute magnitudes listed in Table 1 are from 2016 February.



### 5.2.2. Rotational Period versus Dynamical Class

The NEO population is traditionally divided into four sub-categories: (i) *Amor* with a semimajor axis  $a > 1$  AU and a perihelion distance  $q$  where  $1.017 < q < 1.3$  AU, (ii) *Apollo* with  $a > 1$  AU and  $q < 1.017$  AU, (iii) *Aten* with  $a < 1$  AU and an aphelion distance  $Q > 0.983$  AU, and (iv) *Atira* with  $a < 1$  AU and an aphelion distance  $Q < 0.983$  AU. Atira NEOs, with orbits entirely interior to the Earth's, are difficult to detect and make up such a small fraction of the known NEO population ( $\ll 1\%$ ) that we do not consider them further here. As of 2016 April, the MPC cataloged 6080 Amor ( $\sim 43\%$  of the entire NEO population), 7038 Apollo ( $\sim 50\%$ ), and 1048 Aten ( $\sim 7\%$ ) NEOs. Based on de-biased distributions, Bottke et al. (2002) estimated that 62% of known NEOs are Apollo, 32% are Amor, and 6% are Aten. Here, we report 39 Apollo ( $\sim 46\%$  of our sample), 36 Amor ( $\sim 43\%$ ), and 10 Aten ( $\sim 11\%$ ). In spite of our focus on low  $\Delta v$  objects, the distribution of our targets within each of these dynamical classes is reasonably close to the de-biased relative fractions in Bottke et al. (2002). Recent estimates by Greenstreet et al. (2012) are consistent with Bottke et al. (2002) results, but Mainzer et al. (2012) estimates differ a little with an Aten population of  $8 \pm 4\%$ ,  $55 \pm 18\%$  for the Apollo group and  $37 \pm 16\%$  for the Amor sample.

Figure 6 shows all NEOs reported in the LCDB as well as MANOS objects. Traditionally, the distribution of fast and small rotators is more extended in the Apollo sub-population as compared to the Amors. However, MANOS is finding a significant number of small, fast rotating Amors which do not appear in the LCDB. This could be attributable to our use of large aperture facilities and the corresponding ability to probe small Amors, which often are fainter than the observational limits of smaller telescopic facilities. This trend is probably due to an observational bias. We performed a 2D Kolmogorov–Smirnov (KS) test to compare the three data sets and find if the samples are significantly different (or not) from one another. The KS test estimates the maximum deviation between the cumulative distribution of both data sets to test the similarity (or not) between the two distributions (Df). The significance level of the KS test is a value between 0 and 1. Small values show that the cumulative distribution of the first data set is significantly different from the second data set. Comparing the Amor population to the Apollo population, we obtained a value of Df = 0.11, and a significance level of 0.01, indicating that the two samples are not significantly different, whereas the Aten population compared to the Apollo group gave a Df = 0.08 and a significance level of 0.72, suggesting that the populations are not significantly different. However, we must point out the limited number of Aten asteroids with a measured rotational period.

### 5.3. Axis Ratio and Light curve Amplitude

Estimating the axis ratio of an object from its light curve amplitude is useful to constrain the object elongation.

The observed light curve of a minor body depends on the geometrical circumstances during the observing run. Three angles have to be considered: (i) the *phase angle*  $\alpha$  is the angular distance between the Sun and the observer as seen from the asteroid, (ii) the *viewing (or aspect) angle*  $\xi$  is the angle between the rotation axis and the line of sight, and (iii) the *obliquity* is the angle between the spin vector and the orbital

plane. Figure 1 of Barucci & Fulchignoni (1982) summarizes these angles.

Based on Binzel et al. (1989, p. 416), if we assume NEOs are triaxial ellipsoids with axes  $a > b > c$  rotating along the  $c$ -axis, the light curve amplitude ( $\Delta m$ ) varies as a function of the viewing angle  $\xi$  as:

$$\Delta m = 2.5 \log\left(\frac{a}{b}\right) - 1.25 \log\left(\frac{a^2 \cos^2 \xi + c^2 \sin^2 \xi}{b^2 \cos^2 \xi + c^2 \sin^2 \xi}\right). \quad (4)$$

The lower limit for the object elongation ( $a/b$ ) is obtained assuming an equatorial view ( $\xi = 90^\circ$ ):

$$\Delta m_{\max} = 2.5 \log\left(\frac{a}{b}\right) \rightarrow \frac{a}{b} \geq 10^{0.4 \Delta m}. \quad (5)$$

However, this approach does not consider the phase angle effect, and  $\Delta m$  from the previous equation is the light curve amplitude obtained only during a given observing run (i.e., observation at a certain phase angle, obliquity, and viewing angle). The relation between light curve amplitude and phase angle is well known (Gehrels 1956) (see Muinonen et al. 2002, p. 123 for a complete review). This relation results in an overestimation of the true axial ratio of the object. Only light curves obtained at very different phase angles can be used to correct the amplitude ( $\Delta m$ ). In general, phase curves are not available for small NEOs, so an approximation has to be used. The light curve amplitude can be corrected as follows:

$$\Delta m(\alpha = 0^\circ) = \frac{\Delta m(\alpha)}{1 + s\alpha} \quad (6)$$

where  $s$  is the slope that correlates the amplitude with the phase angle, and  $\Delta m(\alpha = 0^\circ)$  is the light curve amplitude at zero phase (Zappala et al. 1990). Combining Equations (4) and (5), and assuming a viewing angle of  $90^\circ$ , an obliquity of  $0^\circ$ , and a phase angle  $\alpha$ , we obtain:

$$\frac{a}{b} \geq 10^{0.4 \Delta m(\alpha)/(1+s\alpha)}. \quad (7)$$

Analyzing light curves of more than 30 asteroids from different taxonomic types (S, M, and C), Zappala et al. (1990) concluded that the slope ( $s$ ) depends on the taxonomic type. They found a slope of  $0.013 \text{ mag deg}^{-1}$  for M-type asteroids,  $s = 0.015 \text{ mag deg}^{-1}$  for C-type and,  $s = 0.030 \text{ mag deg}^{-1}$  for S-type. Based on numerical models, Gutiérrez et al. (2006) found different slopes depending on the object's topography, and surface scattering properties. They suggested an upper limit of  $0.03 \text{ mag deg}^{-1}$ . We chose a slope of  $0.03 \text{ mag deg}^{-1}$  for the purpose of our work.

In Figure 7, the axis ratio ( $a/b$ ) of MANOS objects has been corrected for this phase angle effect. The mean  $a/b$  ratio without phase angle correction is 1.54, whereas the phase angle correction gives a mean ratio of 1.23. The maximum axis ratio is obtained for 2015 SO<sub>2</sub> with  $a/b = 4.6$  (without phase angle correction), and  $a/b = 1.7$  with correction for observed phase angle of about  $60^\circ$ .

A weak correlation between axis ratio and rotational period has been noticed in the NEO population for objects with a diameter less than 60 m, though this result may be influenced by low number statistics (Hatch & Wiegert 2015). Similarly, for small Main Belt asteroids with diameters less than 1 km, fast-rotating asteroids (with period  $< 2.3$  hr) have a tendency toward low amplitudes relative to slow rotators (Nakamura



et al. 2011). We examined our sample for this weak correlation. In Figure 7, MANOS results and Hatch & Wiegert (2015)<sup>16</sup> data are plotted. We corrected the phase angle effect for both samples and plotted the axis ratio at  $\alpha = 0^\circ$  ( $a/b$  ( $\alpha = 0^\circ$ )). Only objects with a diameter less than 60 m are considered (i.e., objects with an absolute magnitude higher than 23.5, assuming an albedo of 0.2). We find an insignificant correlation between axis ratio and rotational period in our sample (linear fit<sup>17</sup> has a  $R^2$  of 0.0002). Merging the MANOS and Hatch & Wiegert (2015) data, the correlation is still very weak ( $R^2 = 0.073$  for the linear fit). For axis ratio versus absolute magnitude, we found that small objects seem to be more spherical. However, this tendency is also very weak. The linear fit to MANOS results has  $R^2 = 0.0159$  and we find  $R^2 = 0.0083$  for the MANOS + Hatch & Wiegert (2015) data.

We also looked for light curve amplitude versus size tendency according to the object's dynamical class. The Apollo group has a mean light curve amplitude of  $\sim 0.2$  mag that is roughly constant across all sizes. The Amor group indicates a weak correlation between amplitude and absolute magnitude. The Atens show an anti-correlation, but this sample is too small ( $N = 6$ ) to draw any reliable conclusions.

## 6. CONSTRAINTS FOR INTERNAL STRUCTURE OF NEOS

A gravitationally bound strengthless rubble pile cannot spin faster than  $\sim 2.2$  hr without disrupting (Pravec et al. 2002, p. 113). However, very small NEOs can rotate with periods shorter than 2.2 hr. In fact, many have rotational periods of as little as a few minutes. Such rotations are so fast that rubble piles without cohesion could not be held together by self-gravity. A physical interpretation of these fast rotators is that they are objects bound through some combination of cohesive and/or tensile strength rather than gravity. The clear distinction between fast spinning and small-sized asteroids to larger bodies with slower spins, is thought to be related to internal structure. Objects larger than  $\sim 200$  m are interpreted as collections of rocks, boulders, and dust loosely consolidated by gravity alone and are therefore often referred to as “rubble piles” (Chapman 1978). The fact that asteroids smaller than  $\sim 200$  m can rotate much faster suggests they are monolithic in nature and might constitute the blocks from which rubble piles are made. Alternatively, these small-sized asteroids with extremely fast rotation might be “rubble piles,” held together by strong cohesion controlled by van der Waals forces and friction between constituent regolith grains (e.g., Holsapple 2007; Goldreich & Sari 2009; Scheeres et al. 2010; Sánchez & Scheeres 2014). Cohesion forces of 100–1000 Pa were measured within lunar samples returned by the Apollo astronauts (Mitchell et al. 1974). Sánchez & Scheeres (2014) suggested that the cohesive strength of sampled asteroid (25143) Itokawa is  $\sim 25$  Pa based on its measured grain-size. These values are lower than the tensile stress of meteoritic material by at least two orders of magnitude (see Table 4 of Kwiatkowski et al. 2010b). Since meteorites are monolithic and not to be considered as rubble piles, constraining the cohesion values of fast rotating NEOs can allow us to determine whether

an asteroid has a monolithic nature, or can survive as a rubble pile.

This test can be performed by applying the Drucker–Prager yield criterion on NEO parameters. This criterion calculates the minimal shear stress in a rotating ellipsoidal body at breakup taking into account its size, density and spin. Here we use the formalism published by Holsapple (2004, 2007) and later used in other studies that constrained the cohesion values of a few fast rotating asteroids:  $64^{+12}_{-20}$  Pa for (29075) 1950 DA (Rozitis et al. 2014), 40–210 Pa for the precursor body of the active asteroid P/2013 R3 (Hirabayashi et al. 2014), about 100 Pa for the fast rotator (335433) 2005 UW<sub>163</sub> (Polishook et al. 2016) and 150–450 Pa for (60716) 2000 GD<sub>65</sub> (Polishook et al. 2016).

We applied the Drucker–Prager yield criterion on our MANOS targets and on the LCDB data (only NEOs considered) and compared the resulting minimal cohesion. From the light curves we use the measured rotation periods and the amplitude that we translate to the physical ratio  $a/b$  (using Equation (4)). We assume  $b = c$  in order to derive a conservative lower value for the cohesion. The diameters were derived from the absolute magnitude  $H$  and an assumed fixed albedo of 0.2 (Equation (1)). Density was set to  $2.0\text{--}3.3\text{ g cm}^{-3}$  which is the density of the rubble pile (25143) Itokawa (Fujiwara et al. 2006) and the mean density of ordinary chondrite (Carry 2012), respectively, though the derived cohesion value is hardly sensitive to this density range. We find that  $\sim 70\%$  of the MANOS asteroids have minimal cohesion values of less than 100 Pa which is smaller than the cohesion of the lunar regolith;  $\sim 20\%$  have cohesion similar to that of the Moon (100–1000 Pa), and  $\sim 10\%$  have a minimal cohesion larger than lunar cohesion. Still, the largest minimal cohesion we derive is  $\sim 3000$  Pa, two orders of magnitude smaller than the cohesion measured in meteorites (we used the Almahata Sitta meteorite as a reference, Kwiatkowski et al. 2010b). For comparison,  $\sim 94\%$  of the asteroids in the LCDB list have minimal cohesion values of less than 100 Pa. This difference is most probably due to the size difference between the two samples (the mean diameter of LCDB is 1000 m and is 50 m for the MANOS data). When considering LCDB asteroids that are similar in size to the MANOS objects,  $\sim 80\%$  have minimal cohesion values of less than 100 Pa. It is important to note that none of the LCDB asteroids reaches minimal cohesion values that are comparable to the tensile stress measured in the monolithic meteorites, meaning that we cannot reject the notion that even a single one of them is a rubble pile held by shear stress (i.e., cohesion) against a fast spin. However, the dearth of asteroids with diameters larger than  $\sim 200$  m that rotate faster than  $\sim 2$  hr and are limited by the cohesion lines in Figure 3, makes this notion less likely.

## 7. SUMMARY AND CONCLUSIONS

We present a homogeneous data set composed of 86 objects (data reduced and analyzed the same way). We report rotational periods and lightcurve amplitude for most of them, but in some cases, we only report constraints on these properties.

We report that 70% of our sample shows at least one full rotation or a partial light curve with a period estimate. We report partial light curves for 14% of our sample, i.e., objects that do not show a clear rotation period but do show a clear increase or

<sup>16</sup> Hatch & Wiegert (2015) used data from Whiteley et al. (2002), Kwiatkowski et al. (2010a, 2010b), Hergenrother & Whiteley (2011), Statler et al. (2013).

<sup>17</sup> For a perfect one-to-one correlation,  $R^2 = 1$ .

decrease in magnitude. Finally, 16% of the light curves are flat. Most of the observed objects are small and fast rotators, with  $\sim 50\%$  of objects spinning in less than five minutes.

MANOS found two ultra-fast rotators: 2014 RC, and 2015 SV<sub>6</sub> with rotational periods of 15.8 s and 17.6 s, respectively. Discovery of these objects confirmed that MANOS is highly sensitive to the detection of fast spinning objects thanks to the use of large facilities allowing us to use short exposure time. We also highlight fast rotators in the Amor population, confirming again that our survey is sensitive to fast rotating small NEOs.

We studied rotational frequency distribution according to size, and dynamical class. We noted an excess of both slow and fast rotators that does not allow us to fit a Maxwellian distribution to the observable distribution. Rotational periods are not significantly different in the Amor, Aten or Apollo groups.

Axis ratio corrected from phase angle has been derived for our MANOS sample. No strong correlation between axis ratio and size or axis ratio and period has been found.

Among the 30 mission accessible MANOS targets with complete light curves, 6 objects have rotational periods higher than 2 hr, whereas 3 have periods between 1 and 2 hr. The rest (i.e., 21 objects) have periods ranging from a few seconds up to 1 hr: 10 objects are rotating in less than 5 minutes, 3 objects have period between 5 and 10 minutes, and 8 with period longer than 10 minutes. Their sizes range from 3 to 215 m, i.e., an absolute magnitude of 29.6–20.7.

In conclusion, 33 of our 86 MANOS targets are mission accessible according to NHATS (i.e.,  $\Delta v^{\text{NHATS}} \leq 12 \text{ km s}^{-1}$ , launch window 2015–2040); 26 of these 33 are fully characterized with light curve (partial and flat light curves also considered) and visible spectrum. Only seven of the objects presented here meet the NHATS dynamical criteria and the 1 hr rotation limit (Abell et al. 2009): 2002 DU<sub>3</sub>, 2010 AF<sub>30</sub>, 2013 NJ, 2014 YD, 2015 CO, 2015 FG<sub>36</sub>, and 2015 OV. Assuming a similar rate of object characterization as reported in this paper,  $\sim 1230$  objects (i.e., approximately 10% of the known NEO population) need to be characterized in order to find 100 viable mission targets. Approximately 400,000 NEOs with diameter between 10 m and 1 km are estimated (Tricarico 2016). To find 100 viable mission targets,  $\sim 0.3\%$  of the estimated population need to be characterized. Harris & D’Abramo (2015) estimated a population of  $\sim 8 \times 10^7$  objects in the 10 m–1 km size range, and so  $\sim 0.002\%$  of this population has to be characterized in order to find 100 viable targets. This means that  $\sim 33,000$  NEOs are expected to be mission accessible targets using the Tricarico (2016) estimate, whereas the Harris & D’Abramo (2015) value gives us a total of  $\sim 6,000,000$  objects.

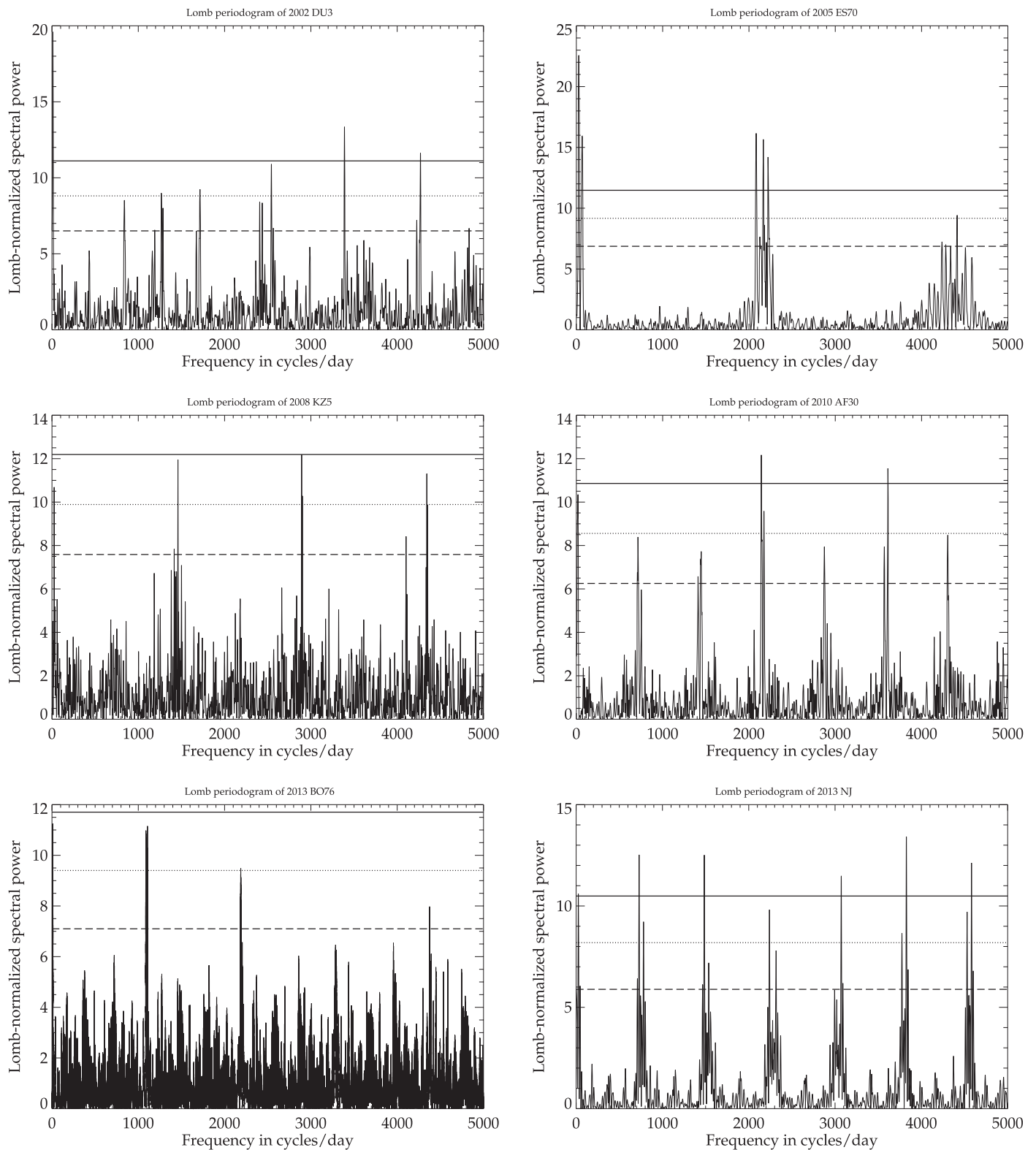
As our main goal is to get a large set of fully characterized objects (light curve, and visible spectra), it is important to complete the study of some objects that have been partially characterized (incomplete/unknown light curve and/or no spectra, Table 2). For most of these objects, their next optical windows are within the next ten years. NHATS generates the

next optical windows through to the year 2040 (see the NHATS webpage for more details). Unfortunately, because of their highly uncertain orbits, most of these objects will be lost by then and current/future surveys will have to re-discover them. It is also important to point out that because of their uncertain orbits, their next windows of visibility can be off as well as their visual magnitude.

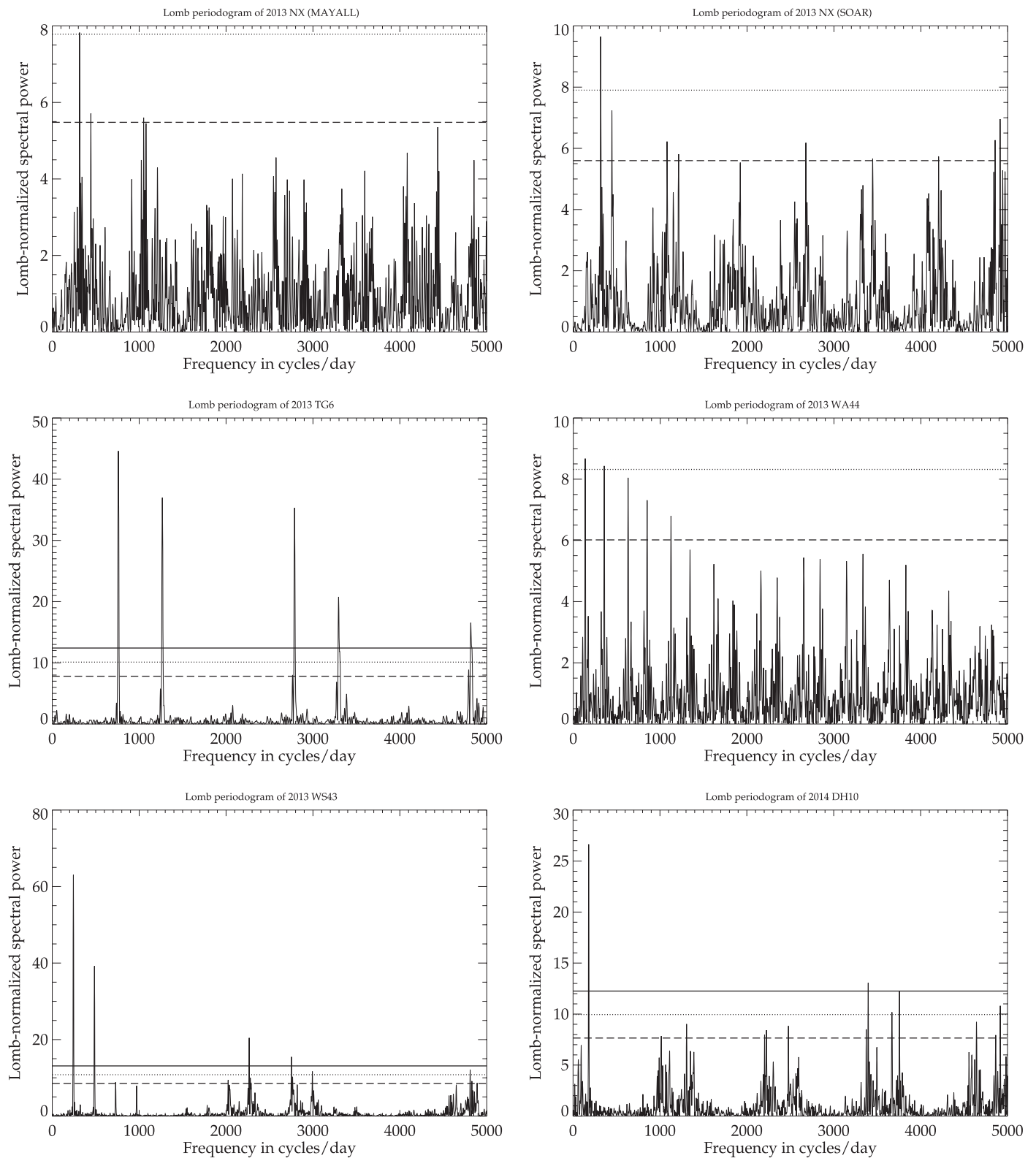
We thank an anonymous referee for her/his careful reading of the paper, and useful comments. We are grateful to the staffs of Discovery Channel Telescope (DCT), the Southern Astrophysical Research (SOAR) telescope, the Kitt Peak telescope, the SMARTS telescope, the Observatory of Sierra Nevada (OSN), and the site of Anderson Mesa. This research was based in part on data obtained at the Lowell Observatory’s Discovery Channel Telescope (DCT). Lowell operates the DCT in partnership with Boston University, Northern Arizona University, the University of Maryland, and the University of Toledo. Partial support of the DCT was provided by Discovery Communications. LMI was built by Lowell Observatory using funds from the National Science Foundation (AST-1005313). This work is also based on observations obtained at the Southern Astrophysical Research (SOAR) telescope, which is a joint project of the Ministério da Ciência, Tecnologia, e Inovação (MCTI) da República Federativa do Brasil, the U.S. National Optical Astronomy Observatory (NOAO), the University of North Carolina at Chapel Hill (UNC), and Michigan State University (MSU). We also used the 1.3 m SMARTS telescope operated by the SMARTS Consortium. Based in part on observations at Kitt Peak National Observatory, National Optical Astronomy Observatory (NOAO Prop. ID:0270; PI:N. Moskovitz), which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation. This research was based on data obtained at the Observatorio de Sierra Nevada which is operated by the Instituto de Astrofísica de Andalucía, CSIC. This research has made use of data and/or services provided by the International Astronomical Union’s Minor Planet Center. Authors acknowledge support from NASA NEOO grant number NNX14AN82G, awarded to the Mission Accessible Near-Earth Object Survey (MANOS). A.T. acknowledges Lowell Observatory funding. D.P. is grateful to the Ministry of Science, Technology and Space of the Israeli government for their Ramon fellowship for post-docs, the AXA Research Fund for their generous post-doc fellowship, and to Prof. Oded Aharonson of Weizmann Institute for his advisory work.

## APPENDIX

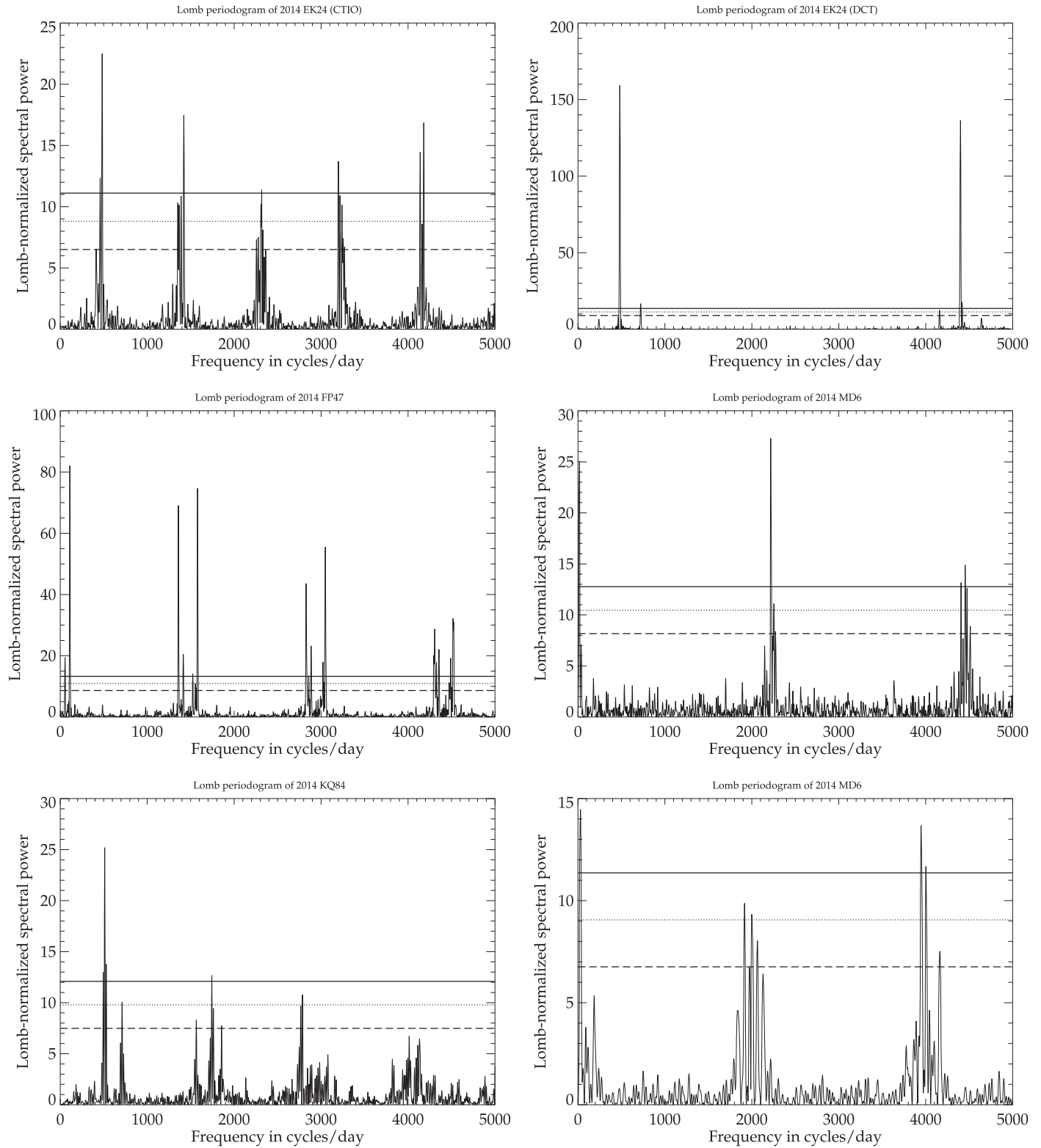
Lomb periodograms and light curves for all objects reported in this work are available in the following [Appendix](#).



**Figure 8.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.

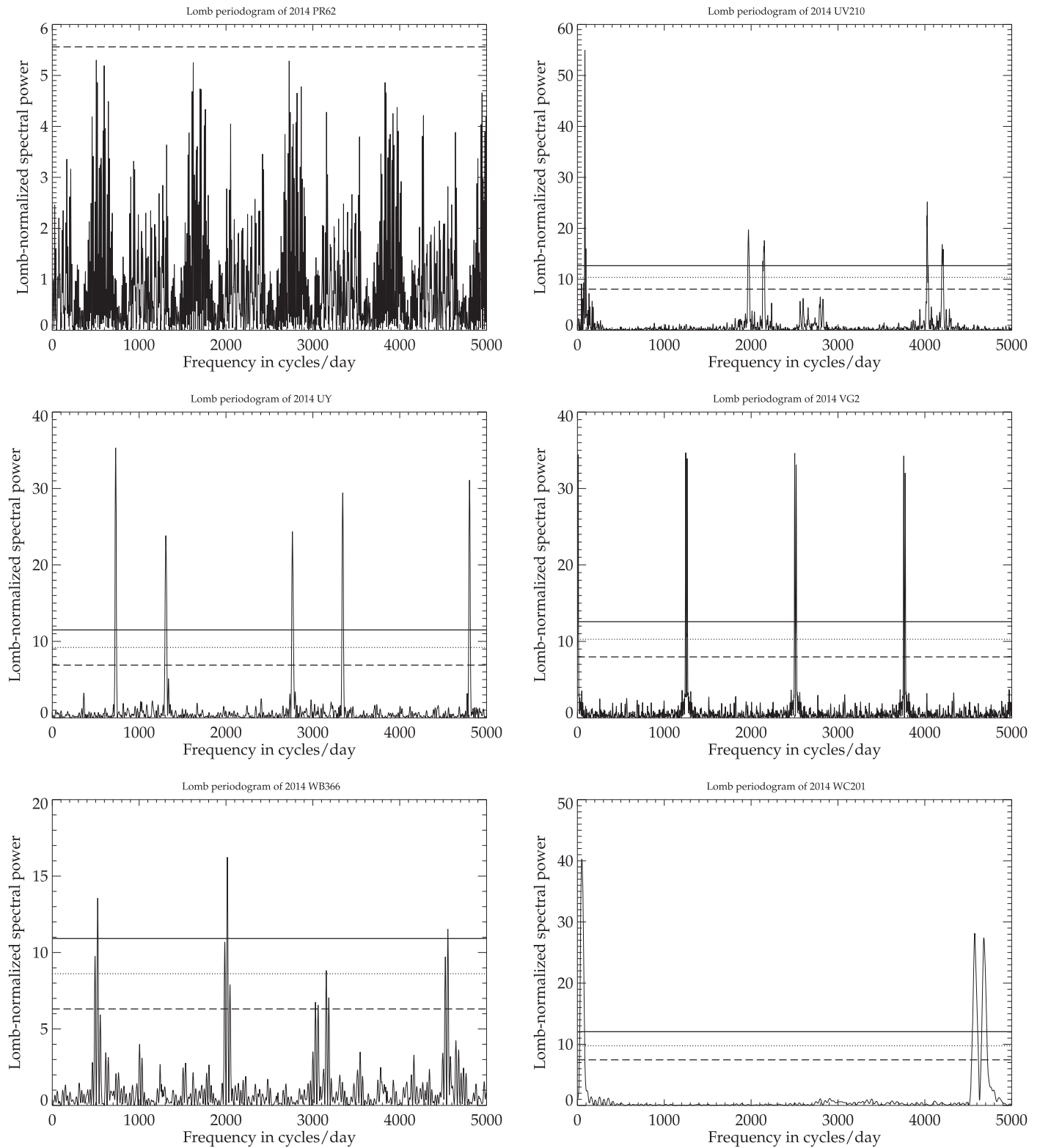


**Figure 9.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.

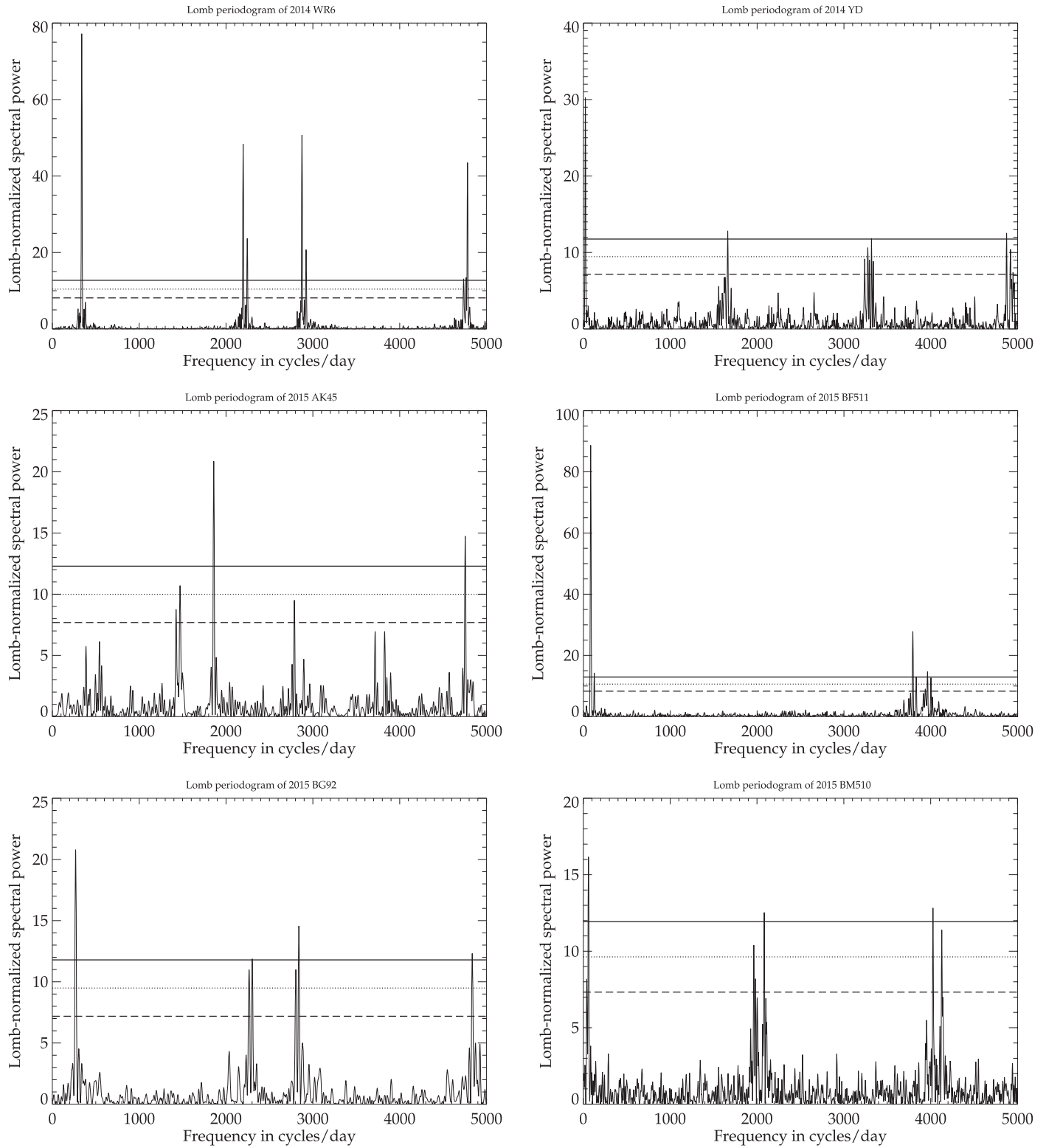


**Figure 10.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.

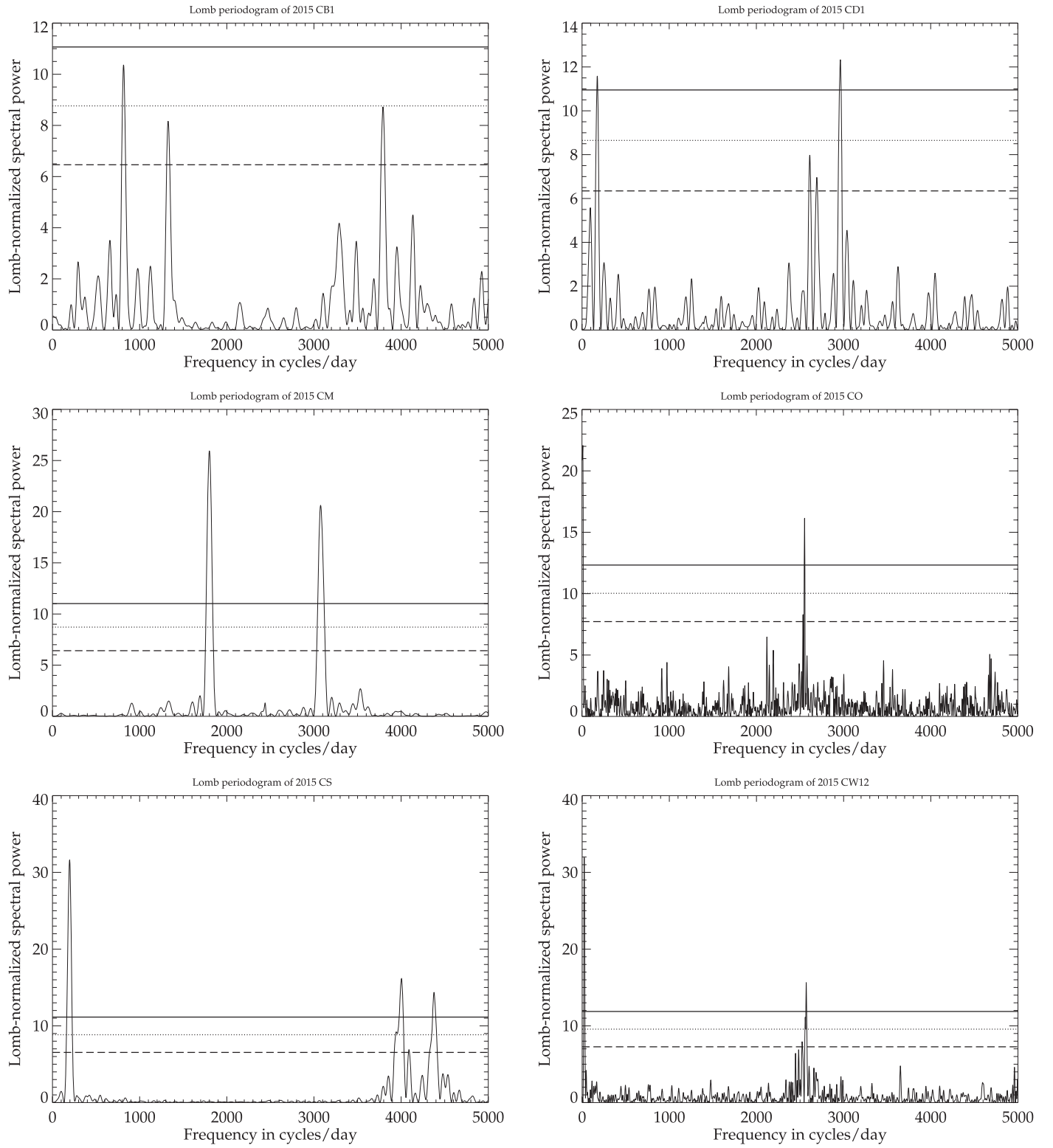




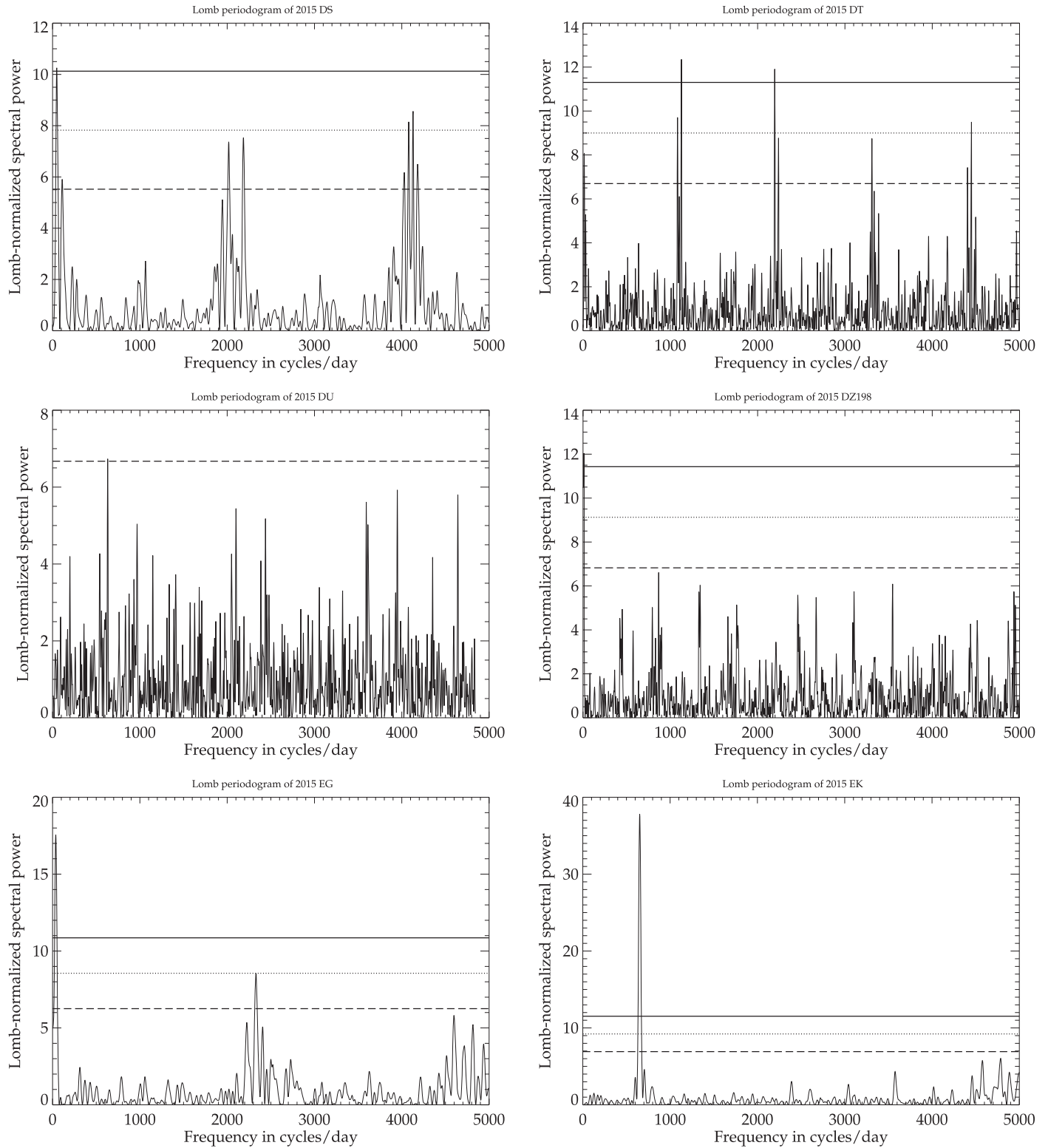
**Figure 11.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.



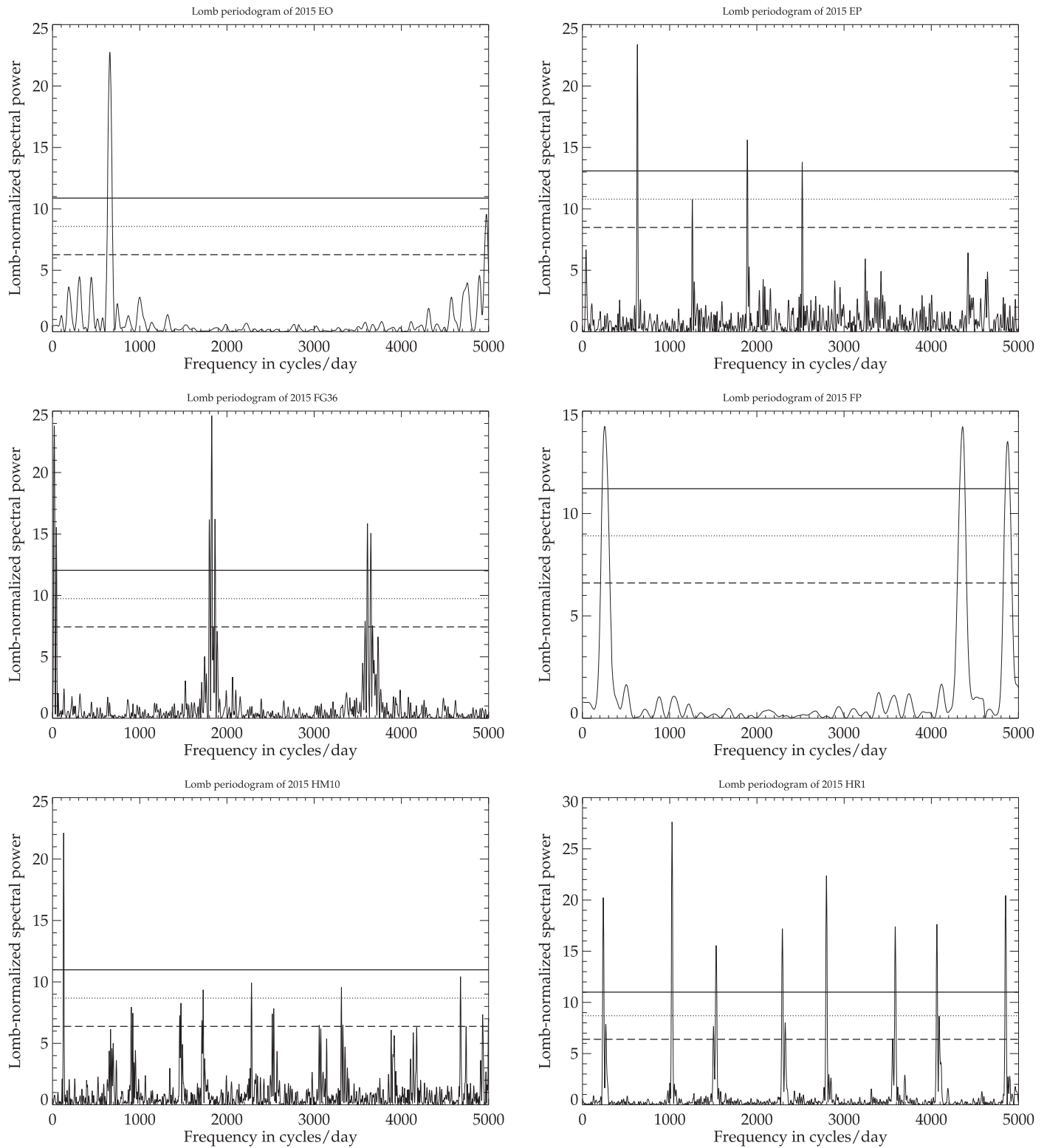
**Figure 12.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.



**Figure 13.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.

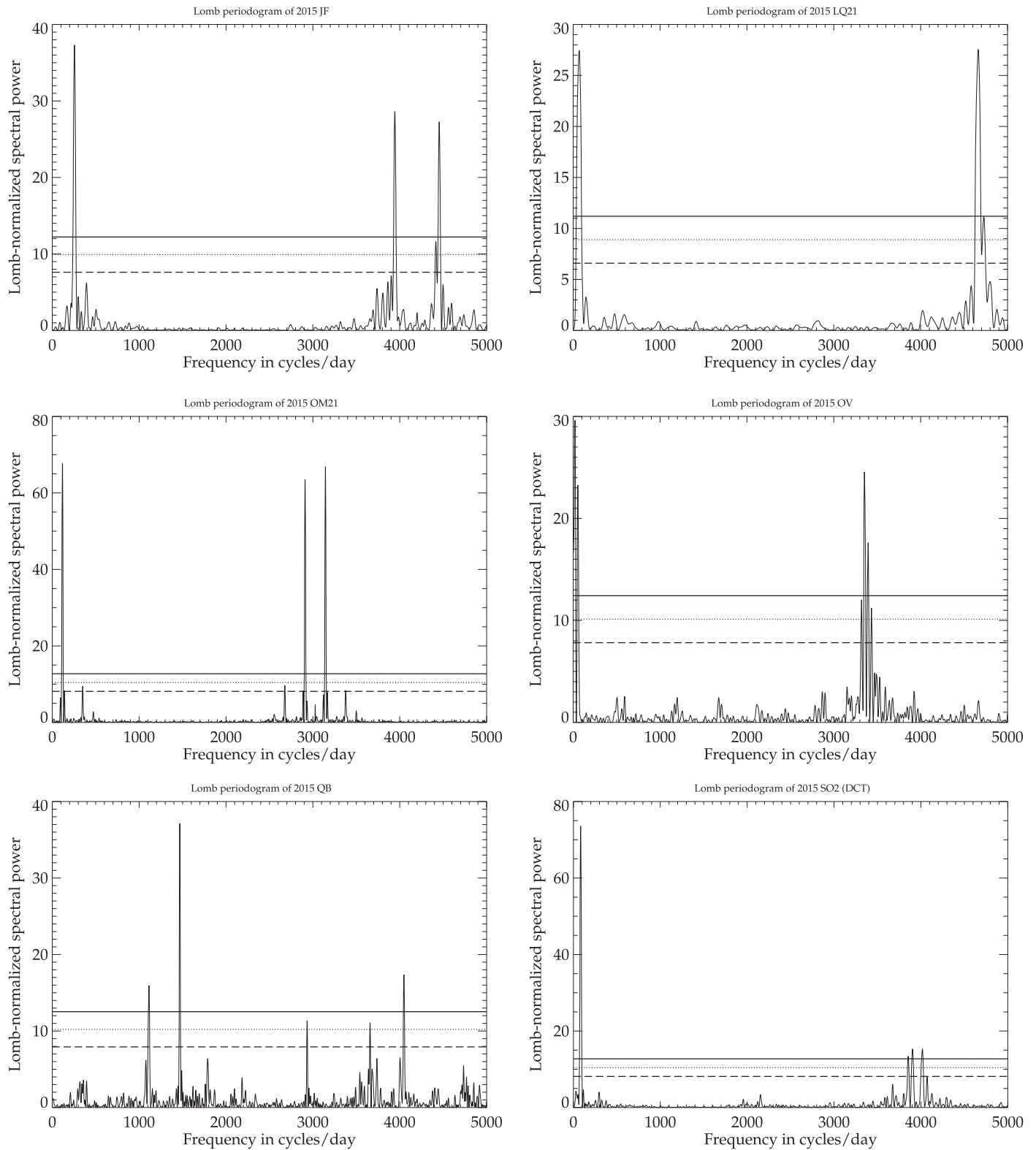


**Figure 14.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.

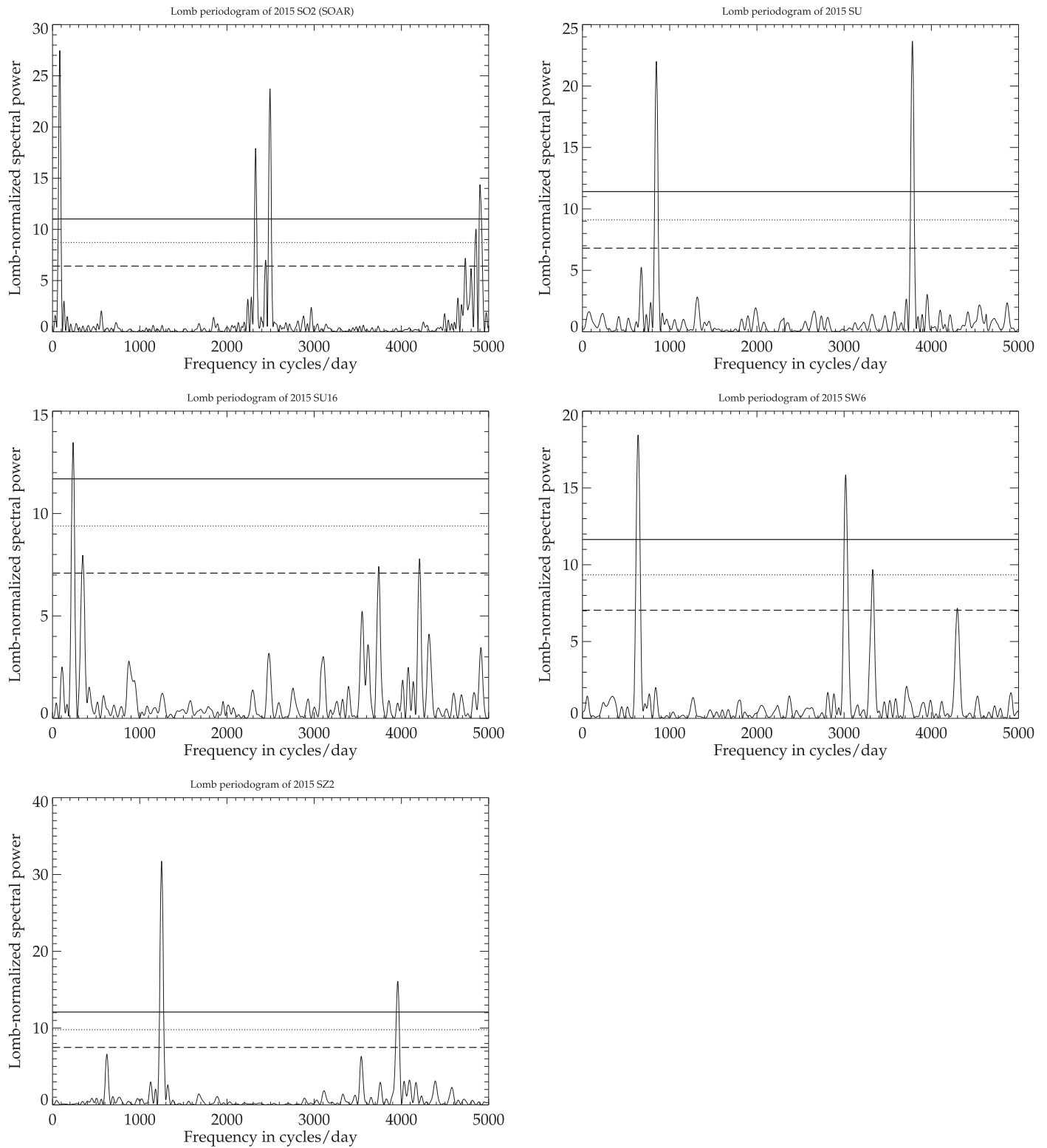


**Figure 15.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.





**Figure 16.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.



**Figure 17.** Lomb-normalized spectral power vs. frequency: Lomb periodograms of MANOS objects are plotted. The continuous line represents a 99.9% confidence level, the dotted line a confidence level of 99%, and the dashed line corresponds to a confidence level of 90%.

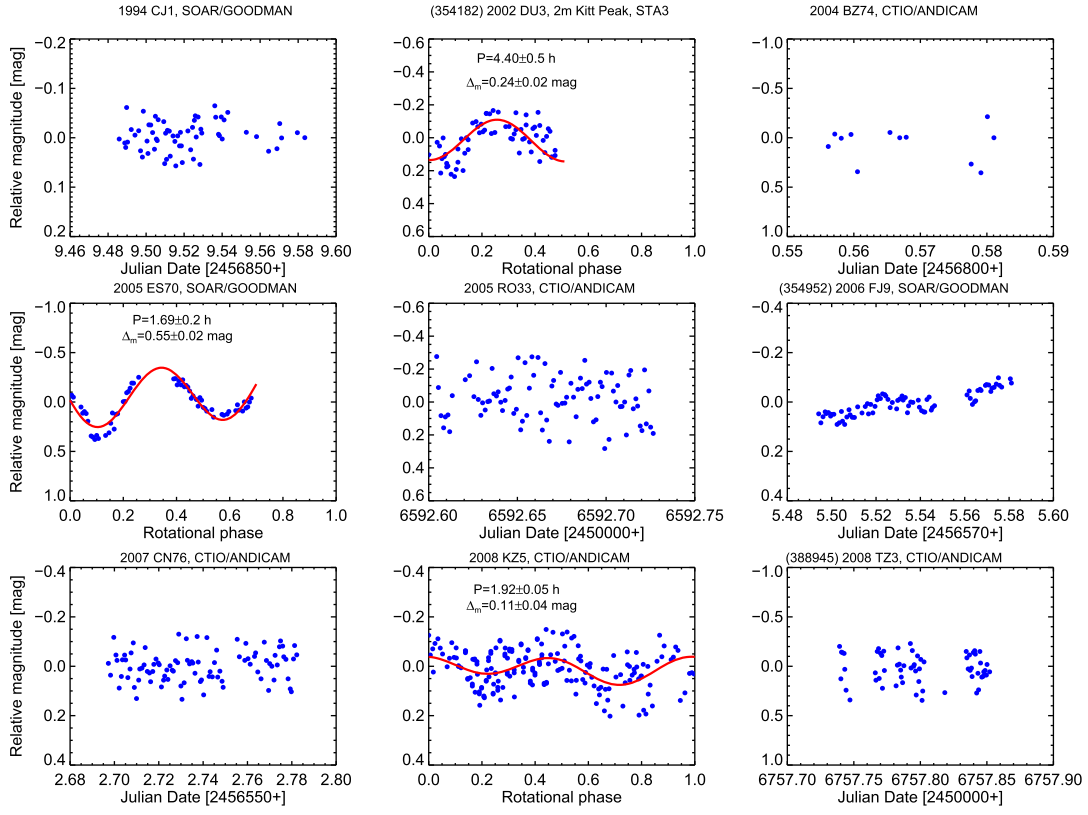


Figure 18. Relative magnitude vs. rotational phase or Julian date: MANOS results are plotted.

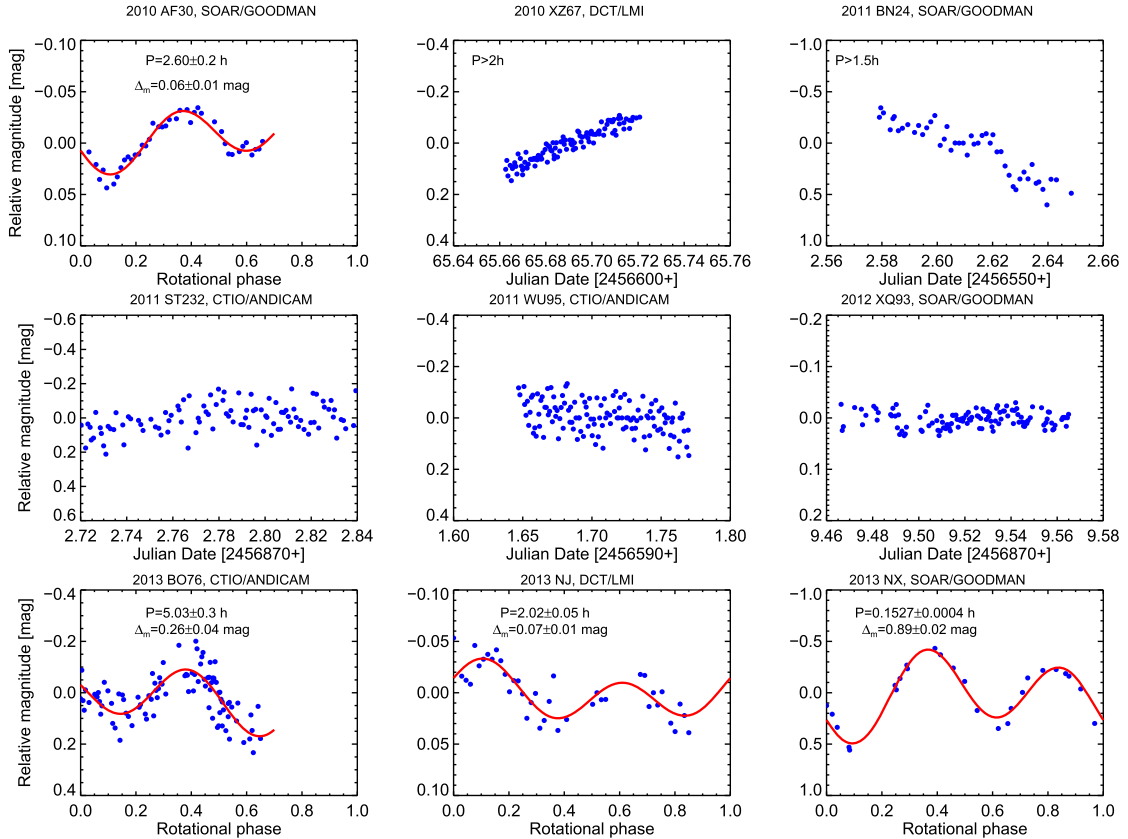


Figure 19. Relative magnitude vs. rotational phase or Julian date: MANOS results are plotted.

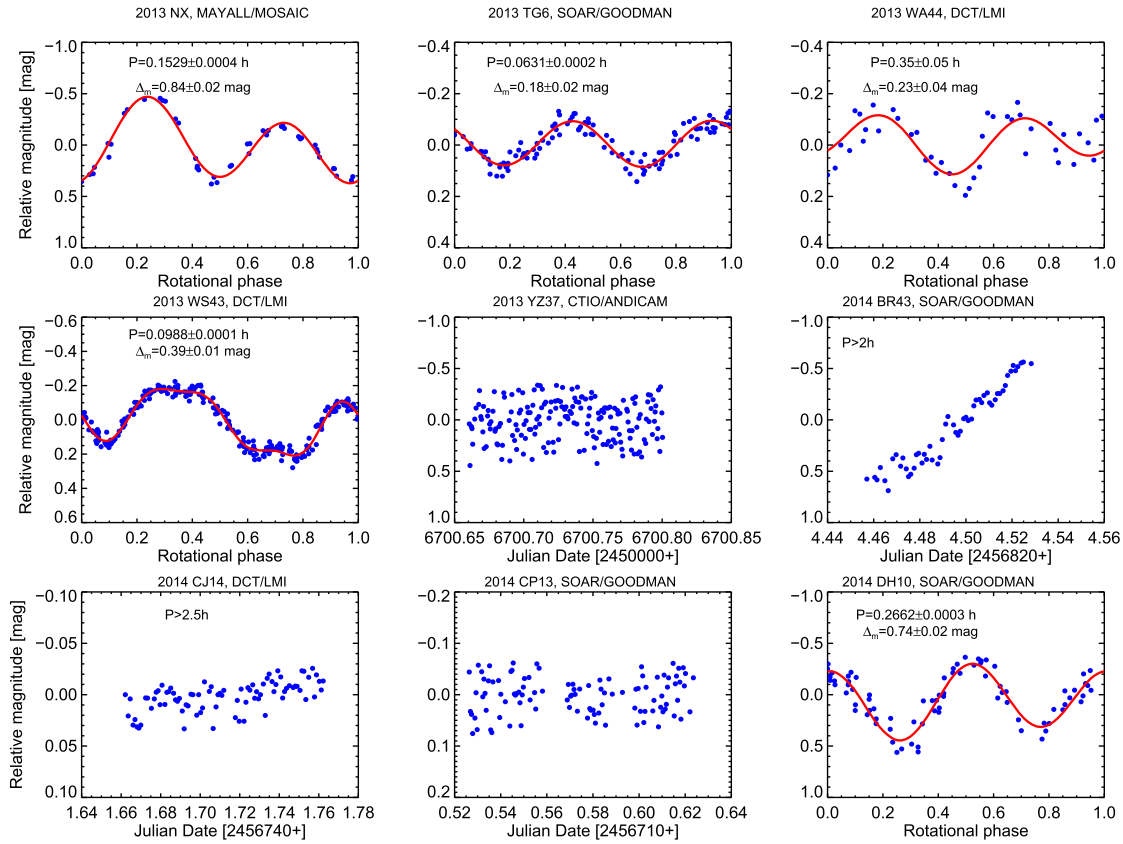


Figure 20. Relative magnitude vs. rotational phase or Julian date: MANOS results are plotted.

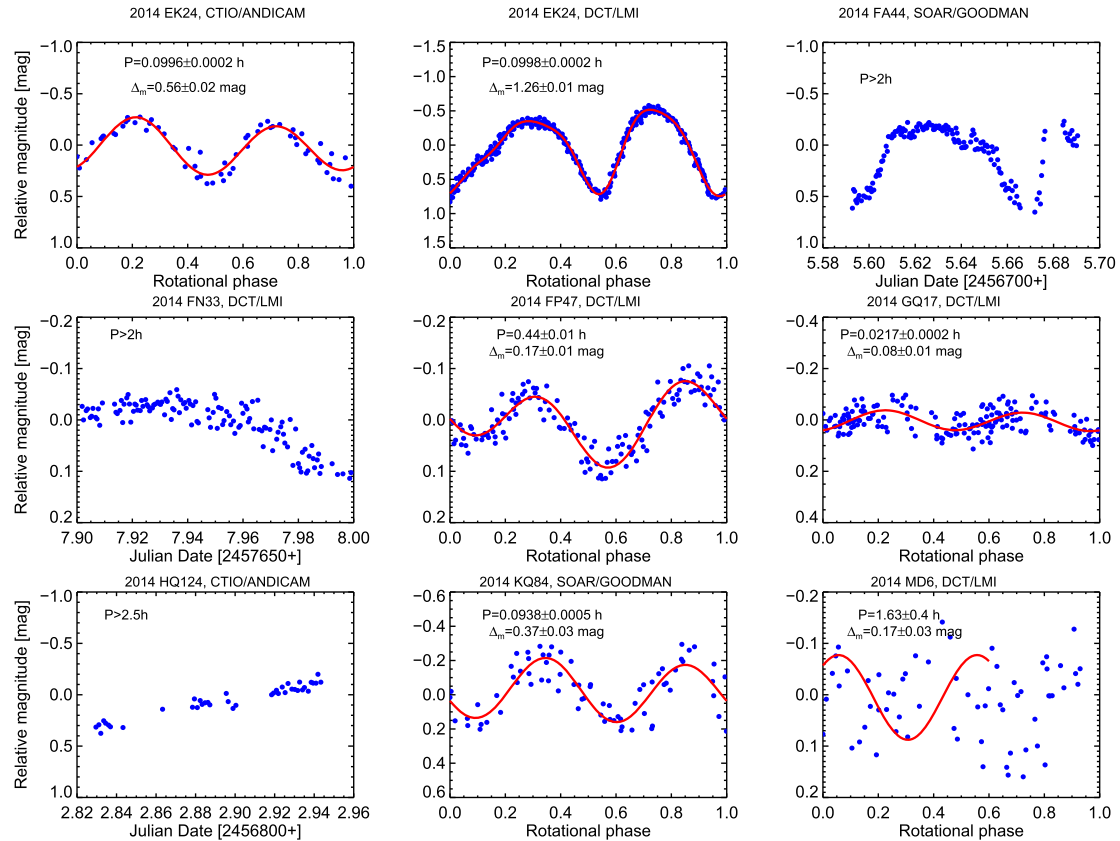


Figure 21. Relative magnitude vs. rotational phase or Julian date: MANOS results are plotted.

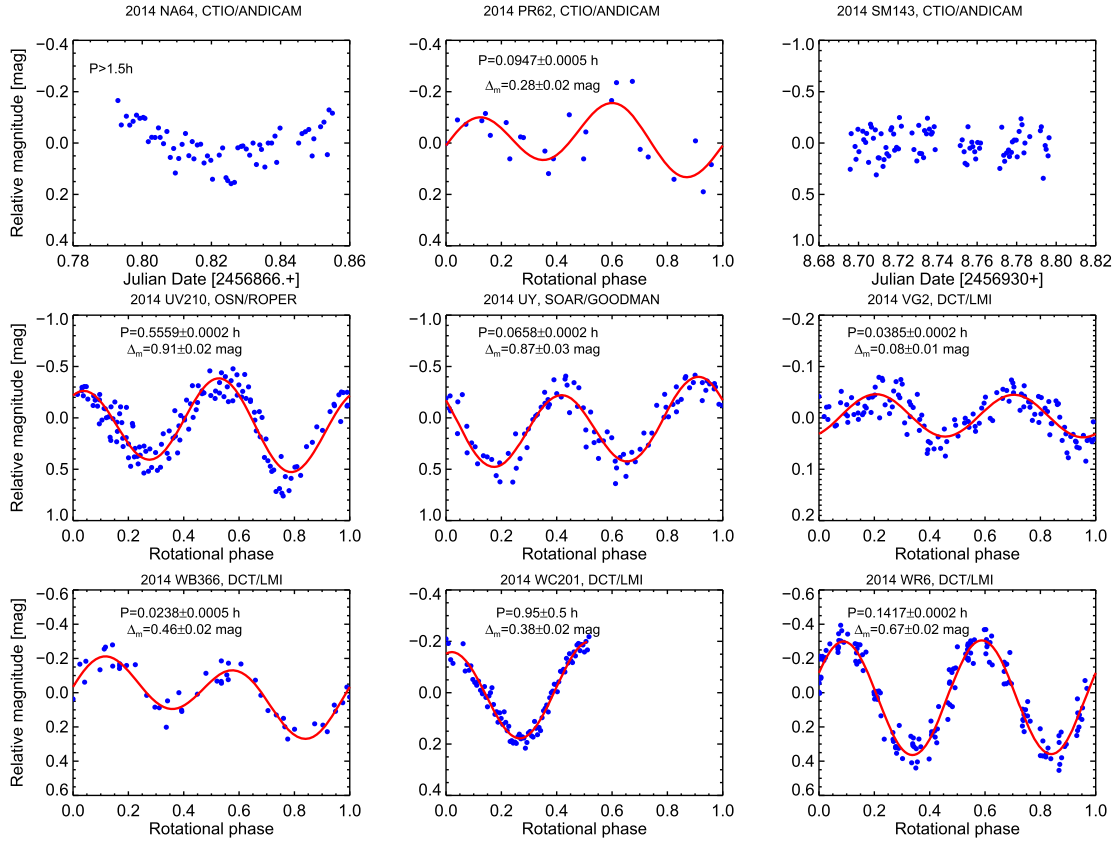


Figure 22. Relative magnitude vs. rotational phase or Julian date: MANOS results are plotted.

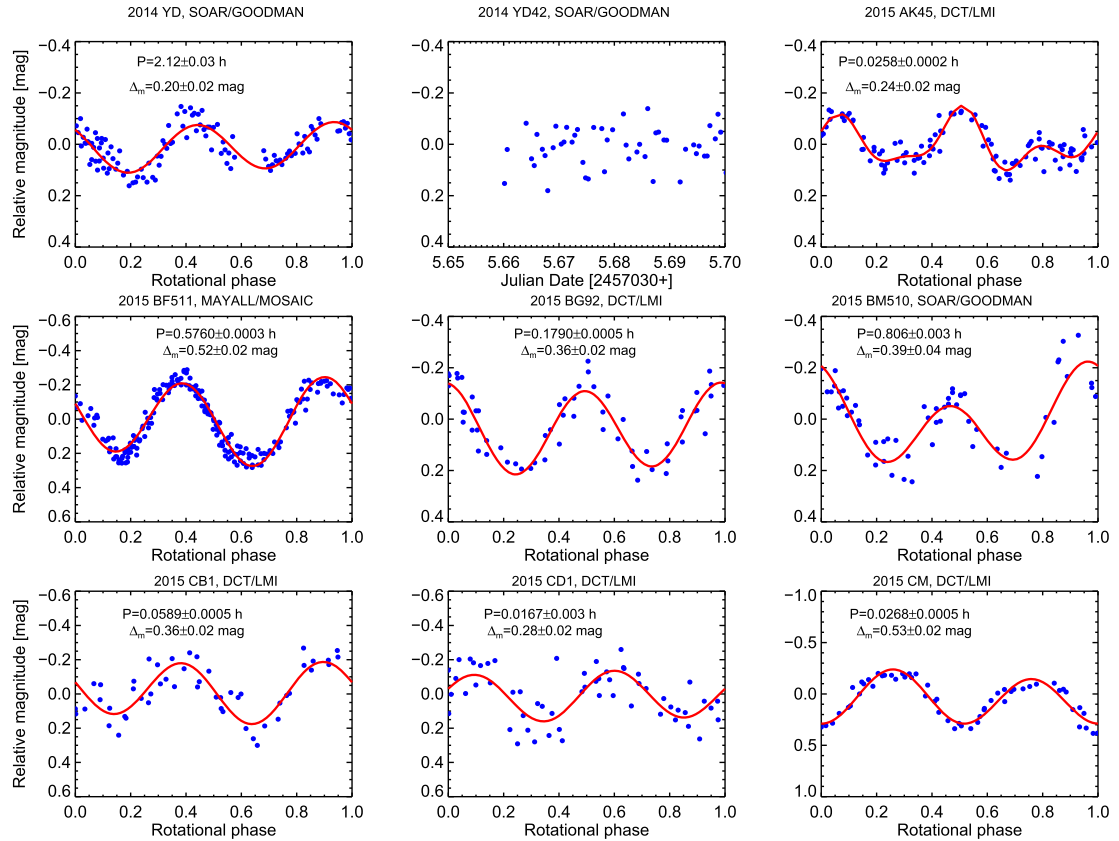


Figure 23. Relative magnitude vs. rotational phase or Julian date: MANOS results are plotted.



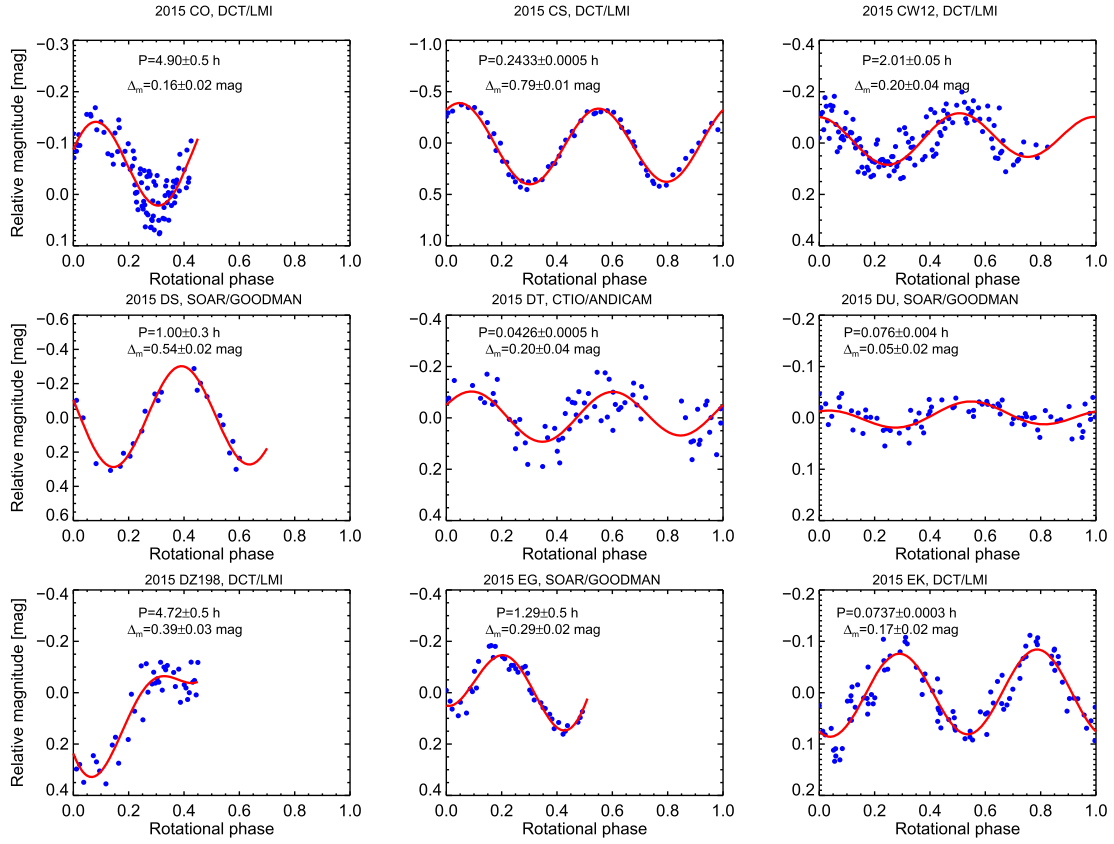


Figure 24. Relative magnitude vs. rotational phase: MANOS results are plotted.

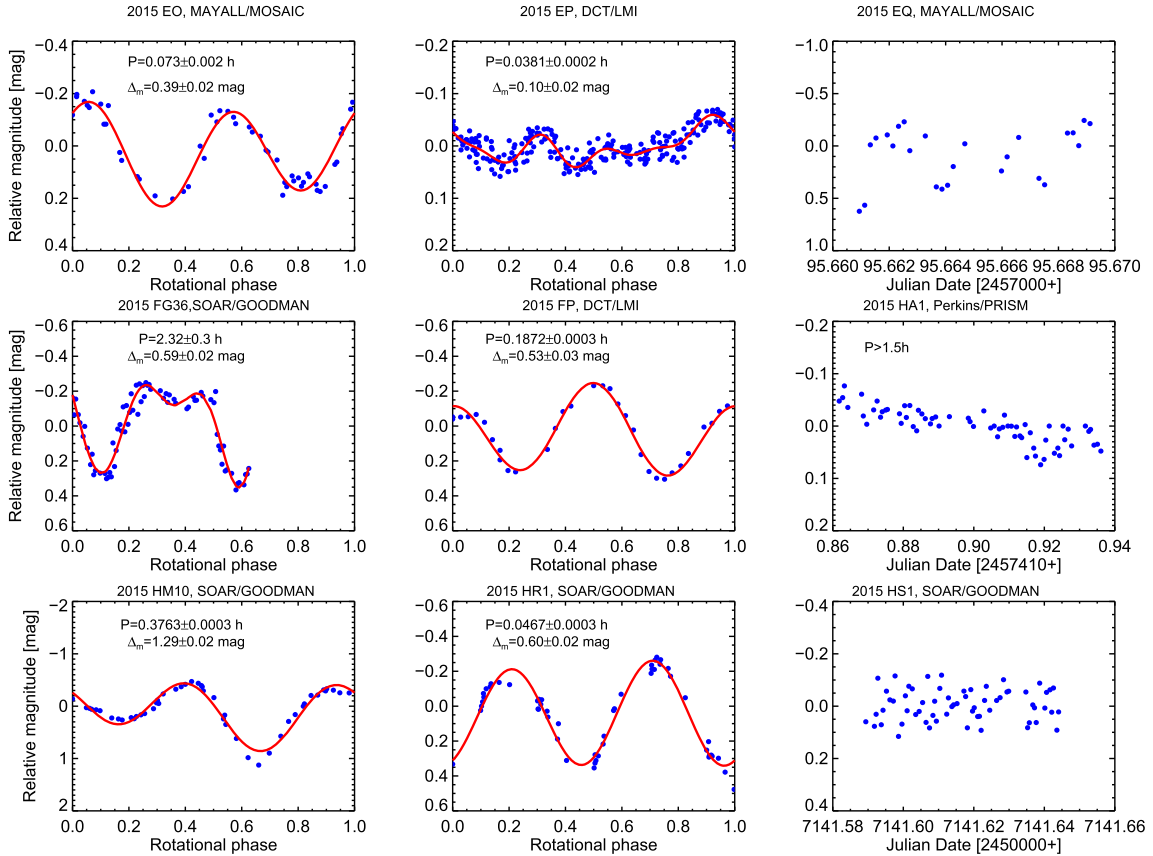


Figure 25. Relative magnitude vs. rotational phase or Julian date: MANOS results are plotted.

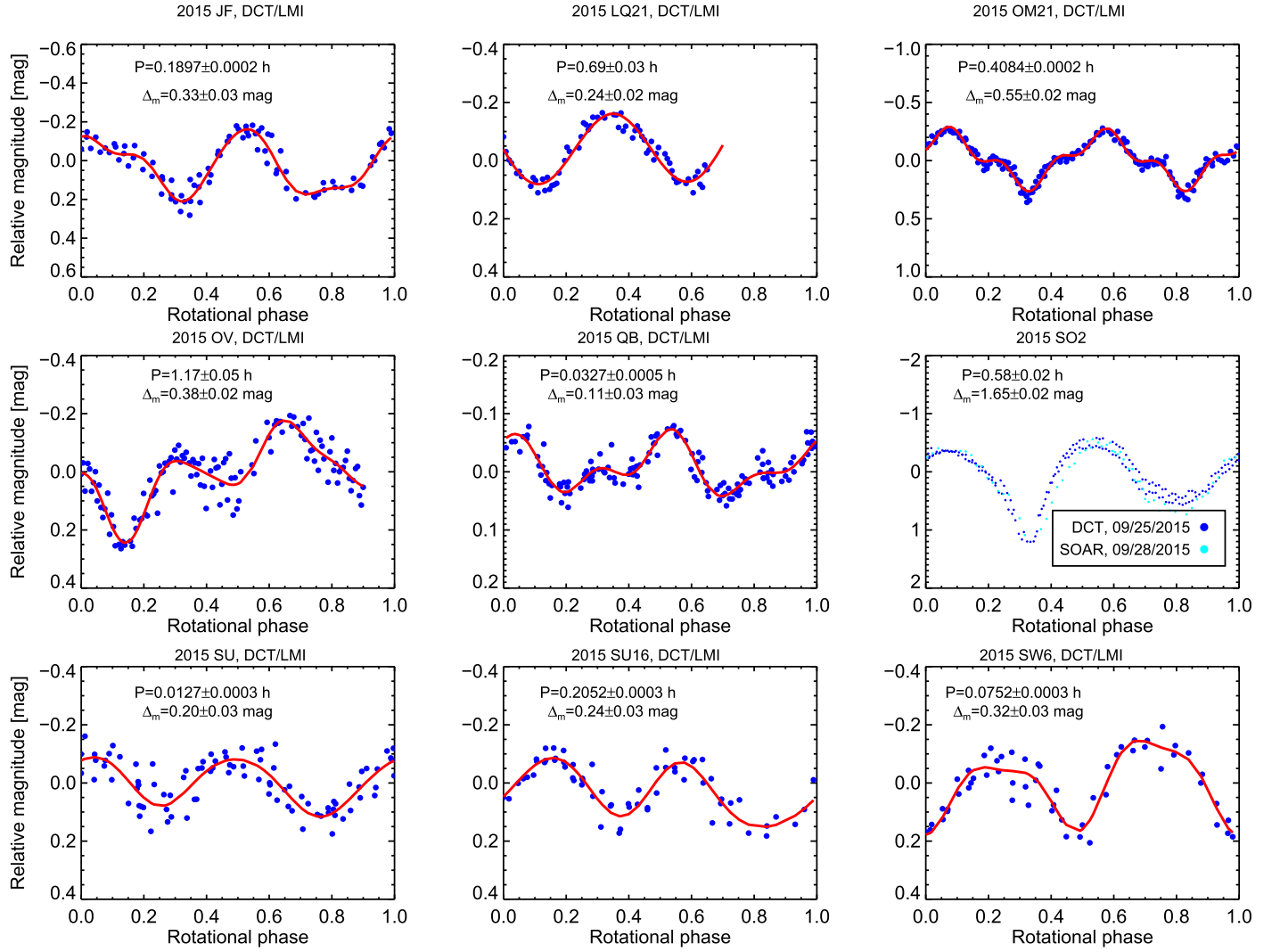


Figure 26. Relative magnitude vs. rotational phase: MANOS results are plotted.

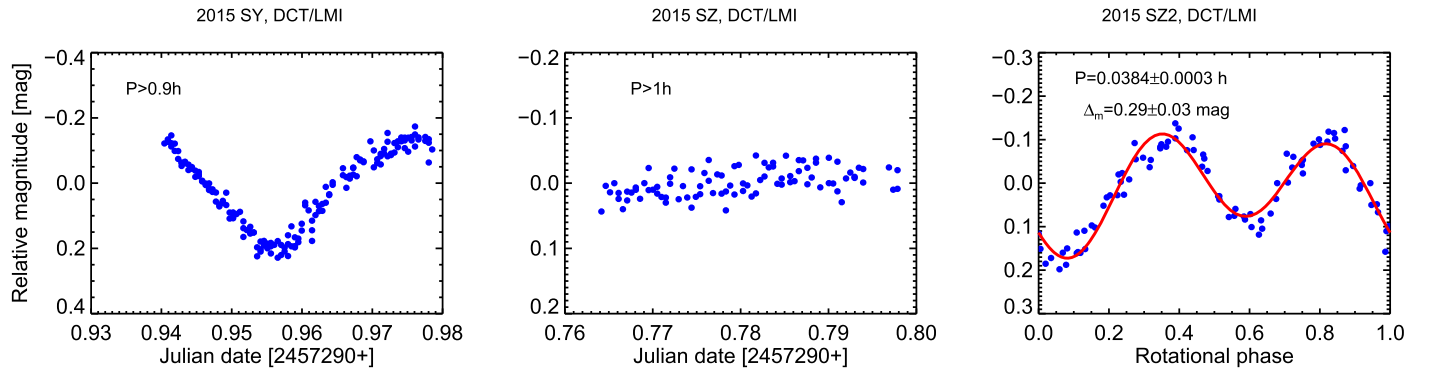


Figure 27. Relative magnitude vs. rotational phase or Julian date: MANOS results are plotted.

## REFERENCES

- Abell, P. A., Korsmeyer, D. J., Landis, R. R., et al. 2009, *M&PS*, **44**, 1825
- Barucci, M. A., & Fulchignoni, M. 1982, *M&P*, **27**, 47
- Benner, L. A., Brozovic, M., Giorgini, J. D., et al. 2014, in AAS Meeting 46 Abstracts #409.01
- Benner, L. A., Busch, M. W., Giorgini, J. D., Taylor, P. A., & Margot, J. J. 2015, in Asteroids IV, ed. P. Michel, F. E. DeMeo, & W. F. Bottke (Tucson, AZ: Univ. Arizona Press), 165
- Binzel, R. P., Farinella, P., Zappala, V., & Cellino, A. 1989, in Asteroids II (Tucson, AZ: Univ. Arizona Press), 416
- Binzel, R. P., Lupishko, D., di Martino, M., Whiteley, R. J., & Hahn, G. J. 2002, in Asteroids III, ed. W. F. Bottke, Jr. et al. (Tucson, AZ: Univ. of Arizona Press), 255
- Binzel, R. P., Morbidelli, A., Merouane, S., et al. 2010, *Natur*, **463**, 331
- Bottke, W. F., Morbidelli, A., Jedicke, R., et al. 2002, *Icar*, **156**, 399
- Bottke, W. F., Jr., Vokrouhlický, D., Rubincam, D. P., & Nesvorný, D. 2006, *AREPS*, **34**, 157

- Busch, M. W., Benner, L. A. M., Naidu, S. P., et al. 2015, in AAS Meeting 47 Abstracts #402.05
- Carry, B. 2012, *P&SS*, **73**, 98
- Chapman, C. R. 1978, NASA Conference Publication, 2053
- Clark, B. E., Helfenstein, P., Bell, J. F., et al. 2002, *Icar*, **155**, 189
- DeMeo, F., & Binzel, R. P. 2008, *Icar*, **194**, 436
- Foster, G. 1995, *AJ*, **109**, 1889
- Fujiwara, A., Kawaguchi, J., Yeomans, D. K., et al. 2006, *Sci*, **312**, 1330
- Galache, J. L., Beeson, C. L., McLeod, K. K., & Elvis, M. 2015, *P&SS*, **111**, 155
- Gehrels, T. 1956, *ApJ*, **123**, 331
- Goldreich, P., & Sari, R. 2009, *ApJ*, **691**, 54
- Greenstreet, S., Ngo, H., & Gladman, B. 2012, *Icar*, **217**, 355
- Gutiérrez, P. J., Davidsson, B. J. R., Ortiz, J. L., Rodrigo, R., & Vidal-Núñez, M. J. 2006, *A&A*, **454**, 367
- Harris, A. W., & D'Abramo, G. 2015, *Icar*, **257**, 302
- Hatch, P., & Wiegert, P. A. 2015, *P&SS*, **111**, 100
- Hergenrother, C. W., & Whiteley, R. J. 2011, *Icar*, **214**, 194
- Hirabayashi, M., Scheeres, D. J., Sánchez, D. P., & Gabriel, T. 2014, *ApJL*, **789**, L12
- Holsapple, K. A. 2001, *Icar*, **154**, 432
- Holsapple, K. A. 2004, *Icar*, **172**, 272
- Holsapple, K. A. 2007, *Icar*, **187**, 500
- Jewitt, D. C. 2002, *AJ*, **123**, 1039
- Jurić, M., Ivezić, Ž., Lupton, R. H., et al. 2002, *AJ*, **124**, 1776
- Kwiatkowski, T., Buckley, D. A. H., O'Donoghue, D., et al. 2010, *A&A*, **509**, A94
- Kwiatkowski, T., Polinska, M., Loaring, N., et al. 2010, *A&A*, **511**, A49
- Lacerda, P., & Luu, J. 2003, *Icar*, **161**, 174
- Lagerkvist, C.-I., Harris, A. W., & Zappala, V. 1989, in Asteroids II (Tucson, AZ: Univ. Arizona Press), 1162
- Levine, S. E., Bida, T. A., Chylek, T., et al. 2012, *Proc. SPIE*, **8444**, 844419
- Lomb, N. R. 1976, *Ap&SS*, **39**, 447
- Mainzer, A., Grav, T., Masiero, J., et al. 2012, *ApJ*, **752**, 110
- Margot, J. L., Nolan, M. C., Benner, L. A. M., et al. 2002, *Sci*, **296**, 1445
- Mazanek, D., Naasz, B., Cichy, B., Reeves, D., & Abell, P. 2015, in European Planetary Science Congress 2015 id.EPSC2015-279, 10, EPSC2015-279
- Mitchell, J. K., Houston, W. N., Carrier, W. D., & Costes, N. C. 1974, Apollo Soil Mechanics Experiment S-200 Final Rep. 7, Space Sciences Laboratory Series 15 (Berkeley, CA: Univ. California Press), 7285 <http://www.lpi.usra.edu/lunar/documents/NASA%20CR-134306.pdf>
- Morbidelli, A., Bottke, W. F., Jr., Froeschlé, C., & Michel, P. 2002, in Asteroids III, ed. W. F. Bottke, Jr. et al. (Tucson, AZ: Univ. Arizona Press), 409
- Muinenen, K., Piironen, J., Shkuratov, Y. G., Ovcharenko, A., & Clark, B. E. 2002, in Asteroids III, ed. W. F. Bottke, Jr. et al. (Tucson, AZ: Univ. Arizona Press), 123
- Nakamura, T., Dermawan, B., & Yoshida, F. 2011, *PASJ*, **63**, 577
- Nyquist, H. 1928, *Transactions of the American Institute of Electrical Engineers*, **47**, 617
- Polishook, D., & Brosch, N. 2009, *Icar*, **199**, 319
- Polishook, D. & 13 colleagues 2016, *Icar*, **267**, 243
- Popova, O. P., Jenniskens, P., Emel'yanenko, V., et al. 2013, *Sci*, **342**, 1069
- Pravec, P., & Harris, A. W. 2000, *Icar*, **148**, 12
- Pravec, P., & Harris, A. W. 2007, *Icar*, **190**, 250
- Pravec, P., Harris, A. W., Kušnirák, P., Galád, A., & Hornoch, K. 2012, *Icar*, **221**, 365
- Pravec, P., Harris, A. W., & Michalowski, T. 2002, in Asteroids III, ed. W. F. Bottke, Jr. et al. (Tucson, AZ: Univ. Arizona Press), 113
- Pravec, P., Harris, A. W., Vokrouhlický, D., et al. 2008, *Icar*, **197**, 497
- Pravec, P., Scheirich, P., Kušnirák, P., et al. 2006, *Icar*, **181**, 63
- Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical recipes in FORTRAN, The art of scientific computing (2nd ed; Cambridge: Univ. Press) c1992
- Richardson, D. C., Bottke, W. F., & Love, S. G. 1998, *Icar*, **134**, 47
- Rozitis, B., MacLennan, E., & Emery, J. P. 2014, *Natur*, **512**, 174
- Rubincam, D. P. 2000, *Icar*, **148**, 2
- Saito, J., Miyamoto, H., Nakamura, R., et al. 2006, *Sci*, **312**, 1341
- Sánchez, P., & Scheeres, D. J. 2014, *M&PS*, **49**, 788
- Scargle, J. D. 1982, *ApJ*, **263**, 835
- Scheeres, D. J., Benner, L. A. M., Ostro, S. J., et al. 2005, *Icar*, **178**, 281
- Scheeres, D. J., Hartzell, C. M., Sánchez, P., & Swift, M. 2010, *Icar*, **210**, 968
- Scheeres, D. J., Ostro, S. J., Werner, R. A., Asphaug, E., & Hudson, R. S. 2000, *Icar*, **147**, 106
- Shoemaker, E. M., & Helin, E. F. 1978, Reports of Planetary Geology Program, **20**
- Statler, T. S., Cotto-Figueroa, D., Riethmiller, D. A., & Sweeney, K. M. 2013, *Icar*, **225**, 141
- Stellingwerf, R. F. 1978, *ApJ*, **224**, 953
- Stetson, P. B. 1987, *PASP*, **99**, 191
- Thomas, C. A., Emery, J. P., Trilling, D. E., et al. 2014, *Icar*, **228**, 217
- Thomas, C. A., Trilling, D. E., Emery, J. P., et al. 2011, *AJ*, **142**, 85
- Tricarico, P. 2016, arXiv:1604.06328
- Warner, B. D., Harris, A. W., & Pravec, P. 2009, *Icar*, **202**, 134
- Whiteley, R. J., Tholen, D. J., & Hergenrother, C. W. 2002, *Icar*, **157**, 139
- Zappala, V., Cellino, A., Barucci, A. M., Fulchignoni, M., & Lupishko, D. F. 1990, *A&A*, **231**, 548